THE EFFECT OF IMPELLER TYPE ON HYDRODYNAMICS AND CONCENTRATION DISTRIBUTION OF COMPOSITE WOOD PELLETS SUSPENDED IN WATER IN A STIRRED REACTOR

by

Negar Saleh

A thesis submitted to
The University of Birmingham
For the degree of
MASTER OF PHILOSOPHY

School of Chemical Engineering
College of Physical and Engineering Science
The University of Birmingham
March 2014

تقدیم با عشق به

پدر و مادر عزیزم که بدون کمکهای بی‌دریغ و پشتیبانی‌های بیکران آنها انجام این کار ممکن نبود و زندگی بدون آنها بی رنگ و بوست و هیچ طراوتی ندارد.

Abstract

In light of the recent research interests in production of pharmaceuticals and chemicals from biomass instead of fossil fuels and oils, researchers have been encouraged to develop and expand the current body of their knowledge regarding the role of woody biomass on manufacturing of chemicals and pharmaceuticals.

Nowadays, it is believed that using biomass has more advantages and benefits than using fossil fuels and oils. So, it should be kept in mind that studies around this subject could have impressive effects on the life of humans and even the planet in the future.

This thesis describes the effect of impeller types on hydrodynamics and concentration distribution of composite wood pellets suspended in water in a stirred reactor. These effects are studied by conducting several experiments in order to examine three types of impellers; six-bladed Rushton turbine impeller, six-bladed pitched blade impeller and helical screw impeller. Then by measuring torque and impeller speeds, which were followed by estimation of power consumption and energy dissipation rates, the results were analysed and evaluated to figure out the most suitable and beneficial type of impeller, which can be used in industries.

At the end of this research, it was found that the most suitable impeller for this study will be evaluated by parameters such as: power consumption, energy dissipation rates, minimum impeller speed and viscosity.

Acknowledgements

The achievement of this thesis has depended on the helps and influences of many people, to whom I owe a countless deal of gratitude and appreciation. Firstly, I would like to express my thankfulness to my supervisor at the University of Birmingham, Prof Andrzej Pacek for his great and valuable guidance throughout the duration of this work and his correction to this thesis.

My gratitude is extended to a very helpful and patient person, Mr. Artur Majewski who helped me every single day that I was working in the laboratory, in order to do my experiments with ease. Also, I should thank Mr. Amir Asghari and Mr. Benyamin Farsani for their help in correcting this thesis.

Secondly, my thanks go to my family specially my parents who were very supportive and kind to me in my studies and without them life does not have any meaning for me. Also I would like to thank my lovely sister who encouraged me to study for an M.Phil and for always being there for me in both happy and sad times.

My special thanks goes to Mr. Rouzbeh Khaffaf Rasouli for being a great support and the best friend. And finally I would like to thank my dear friend Mrs.Tara Jahanian for her constant friendship and the memorable days we have passed together.

Table of Content

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION

1.1 Background

Using biomass as a resource of raw material has numerous applications in industry. Due to the limited amount of fossil fuels available and for the protection of the environment, renewable resources are becoming the focus of significant attention among the modern industries (Wiley-Blackwell, 2009).

Biomass is used to generate heat, electricity and also wide range of chemical products. This is due to several economic and environmental advantages offered by biomass, such as decrease of the consumption and cost of fossil fuels and reduction of emission of green house gases.

On one hand there are many woodlands and biomass resources available in the United Kingdom, which makes using biomass for chemical feedstock favorable. On the other hand, the mixing of biomass, which is necessary for converting biomass to chemicals in the industry, is a challenging topic of recent research. So, it is believed that investigation of "*The effect of impeller type and speed on concentration distribution of composite wood pellets in stirred reactor*" is necessary to develop new methods of converting wood pellets into useful chemicals.

There are two main reasons why investigation of this topic is important. The first is that using biomass instead of fossil fuels and crude oil has many benefits for the environment and it is industrially relevant. The second is the fact that the mixing of rheologically complex multiphase systems is very complex and still not well understood despite the fact that for many years it has been used on industrial scale. So further research is necessary in order to better understand different aspects of multiphase mixing and cover the gaps in the literature, which were not addressed in previous works.

1.2 The Scope of Current Study

The effect of the impeller type and speed on hydrodynamics and concentration of composite wood pellets (commercially known as Brites pellets) suspended in water was investigated in two (solid-liquid) and three (gas-solid-liquid) phase systems. Brites pellets are made from the sawdust and they were selected as solid phase (biomass) and were mixed with water with/without air using three different types of impeller: six-blade Rushton turbine, six-blade pitched blade and helical screw impeller.

The experiments carried out with Rushton turbine and pitched blade impellers were conducted in a fully baffled stirred vessel fitted with an air sparger and torque/impeller speed measurement system. The experiments with helical screw impeller were focused on mixing in solid/liquid system without air passing through it and were carried out in a glass beaker.

The results of all experiments are summarized and discussed through the thesis.

1.2.1 Objectives of this study

There are three main objectives of this work:

1. Investigate the hydrodynamics of suspended wood pellets in water by measuring different parameters such as torque and impeller speed, followed by calculation of power consumptions and energy dissipation rates.
2. Investigate the effect of concentration of suspended Brites wood pellets in water with and without air on the uniformity of suspension and intensity of mixing in order to find the maximum solid concentration at which uniform solid suspension can be formed.
3. Discuss and compare the results of all experiments and compare the results of this study with literature data.

1.3 Thesis Layout

The thesis structure is as follows. The introduction of this thesis is given in CHAPTER 1. A complete literature survey of woody biomass and mixing of multiphase systems necessary for this study is discussed in CHAPTER 2 and CHAPTER 3. The equipment and materials and also experimental procedures are all explained in CHAPTER 4.

CHAPTER 5 covers the results of all experiments, which have been carried out in this work. The results are analyzed and discussed in detail in CHAPTER 6.

CHAPTER 2

Literature Survey (woody biomass)

2.1 Introduction

For the last century, petroleum and other fossil fuels dominated both energy and chemical production (MacKay, Cole et al., 2009). In general, a large amount of organic chemicals manufactured annually all over the world are derived from petroleum. The potential environmental pollution loading through the use and the end-of-life cycle criteria such as pollution, disposal and degradation are massive. So, diminishing pollution caused by petrochemicals is propelling the green technologies, which are becoming more attractive to research. It is inarguable that the decreasing hydrocarbon economy will become unsustainable whereas the cost of crude oil continues to rise and agricultural products see dramatic decreases in world market prices. These developments provide beginnings for renewed interests in the use of biomass as a feedstock for the development of a carbohydrate-based economy as the logical alternative to fossil fuel resources (Lucia, 2007).

Currently, the largest source of biomass is wood (Sagisaka, 2007). Among these available woodlands, there is a huge amount of forest biomass including residues from final cutting and thinning and also low quality logs, which have not been used properly. They would be left in forests due to difficulties of harvesting and transporting costs (Kamimura, Kuboyama et al., 2012). But nowadays, researchers have found out that the importance of wood biomass from forests is rapidly increasing because of its usage in a wide range of industries.

2.1.1 Benefits of using biomass

Cellulosic biomass from plants can be used as a source of raw materials for industrial processes. The use of this biomaterial presents many advantages. Notionally, cellulose as feedstock is cheaper compared to petroleum. Furthermore, not only its use would not affect food supplies and chemicals derived from lignocelluloses, but also it would have a lower influence on the environment than petrochemicals. Moreover, cellulosic biomass is considered carbon dioxide neutral, while its burning does not enter any carbon to the atmosphere beyond what is needed for the plant to grow. This makes biomass usage, a green, environmentally friendly alternative to fossil fuels (Lucia, 2007).

Normally, usage of biomass is a replacement of using electricity from burning fossil fuels for power production, heat generation and fuels. Its usage as a fuel can reduce global warming to a large extent during the phase in which the biomass plants are growing and can store carbon monoxide. Also the usage of biomass can reduce the dependency on fuels and oils imported from other countries. In this case, large amounts of money and time would be saved and the country's or an entity's self sufficiency will be increased (Garcia, 2012). Also, biomass provides a naturally abundant resource, which is sustainable. The bio industry has an environmentally friendly alternative compared to the petroleum industry. The productive use of different biomass allows for lower emissions to the atmosphere while CO_2 from biomass is defined as neutral. Also it could offer a new source of economic growth for countries (Lucia, 2007).

2.2 Wood

The three major elements of wood are: carbon (49% by weight), oxygen (44% by weight), hydrogen (6% by weight). These elements are combined in complex molecules, which are then joined into polymers. These polymers provide the structural integrity of wood. The polymers of wood can be classified into three main types such as cellulose (40-50% of dry weight), hemicellulose (20-35% of dry weight) and lignin (15-35% of dry weight). The proportion of the three polymers can be varied between species. Furthermore, wood contains small quantities of other organic and inorganic compounds which are known as extractives (Audrey, 2012).

2.2.1 Separation of lignin from woody biomass

Nowadays, bio refinery processes targeting at the valorization of the lignocelluloses part of the biomass, which contains of cellulose, lignin and hemicelluloses and produce in analogy to petroleum refinery processes. It has numerous products including chemicals and fuel for energy production (Lange, Decina et al., 2013).

Generally, lignocelluloses bio refinery receives massive amount of lignin, therefore, the development of efficient and sustainable bio refinery process should valorize the lignin not only as energy but also as a resource for preliminary materials for the chemical industries. Remarkably, lignin represents the only renewable source of aromatic fine chemicals. Therefore, there is a very interesting future opportunity of efficient and direct conversion of lignin to discrete molecules or classes of lower-molecular weight aromatic and monomeric building blocks for polymer production (Lange, Decina et al., 2013).

As following figure shows, selective modifications of the polymer lignin itself are appropriate to convert it into a structural base for complex co-polymers with several potential applications (Lange, Decina et al., 2013).

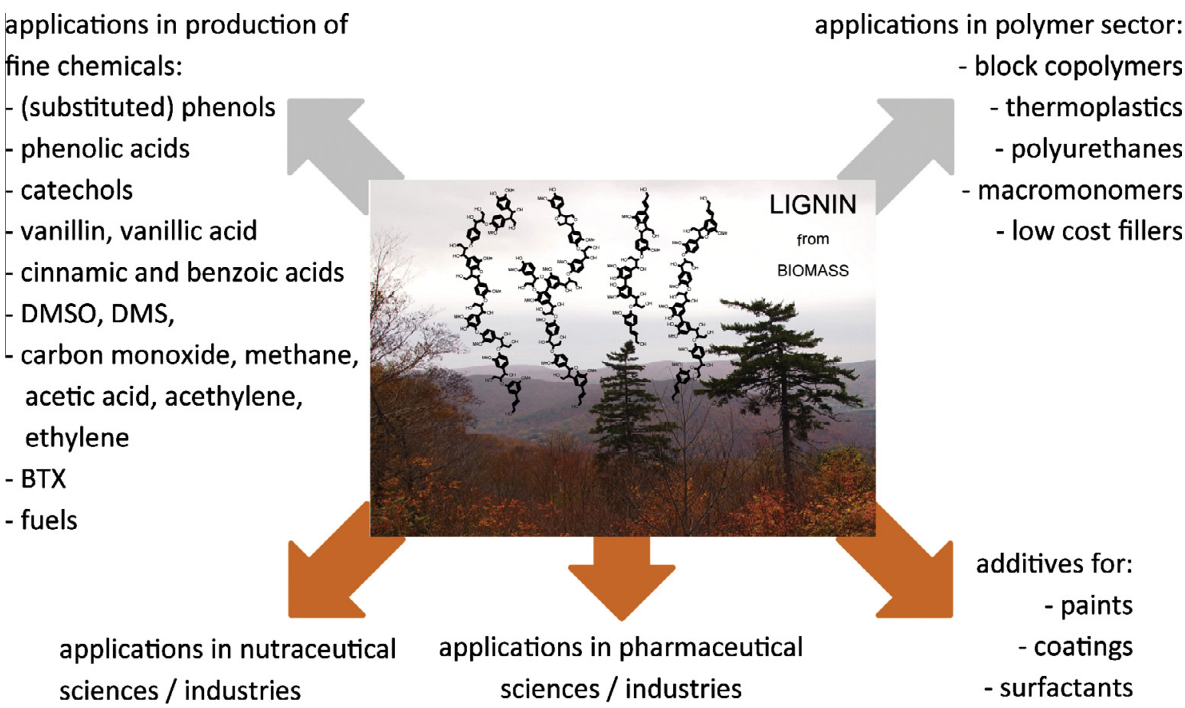


Figure 1 Existing and potential applications of lignin as renewable resource from biomass (Lange, Decina et al., 2013).

2.2.2 Effects of Water on Wood

The properties of wood are strongly dependent on water. Inside the tree, the wood cells are formed in an aqueous environment, and also they have a natural relationship with water. In terms of predicting macroscopic wood performance, considering sorption of water in the cells is very important (Engelund, 2011). The wood cell wall is made from polymers, which are all more or less hydrophilic. In all wood polymers, hydroxyl groups play an important role in attracting water molecules. Also other chemical groups such as carboxyl groups might attract water. Generally, sorption sites are known as all chemical groups capable of attracting water molecules. Most of the sorption sites are found in the hemicellulose followed by cellulose and lignin. Conformational analysis shows that the amorphous nature of hemicellulose and lignin makes all their sorption sites more or less equally energetically encouraging for water molecules. And for cellulose, only the surfaces of micro fibrils are easily accessible for water (Engelund, 2011). Because of the rigid structure of cellulose micro fibrils, the sorption energy of their sorption sites has superior variation than the amorphous wood polymers (Engelund, 2011). As water molecules cannot enter the aggregate cellulose, enlargement happens only in the hemicelluloses and lignin fractions and results in increasing of spaces between micro fibrils. Also, this enlargement will cause increased cell wall dimensions (Engelund, 2011).

The elastic properties of wood polymers are influenced by the breaking of hydrogen bonds by water molecules (Engelund, 2011). Generally, there is a marked weakening effect as water decreases the bonding between fibres and softens the cell walls. The hydrogen bonds between different polymer chains in the crystalline cellulose micro fibrils can break. On one hand, hydrogen bonds form with water instead of polar molecule, so they can get in between of polymer chains. On the other hand, stronger hydrogen bonds are formed between water and cellulose than between cellulose and cellulose. So it is more favorable to make hydrogen bonds with water (Doitpoms, 2006). This softens the cellulose micro fibrils, as they are no longer so strongly bonded to each other and also makes it easier to untangle and therefore stretch the fibres. This reduces the stiffness of wood (Doitpoms, 2006).

2.3 Pulp production

Generally, cellulose is known as the fibrous component of wood, which is used to make pulp and paper and lignin, is called the “glue” which holds wood fibres together. Pulping is the process that decreases wood to a fibrous mat with separating the cellulose from lignin. This process is classified as mechanical, chemical and semi-chemical. The three main chemical pulping methods are known as sulphite, Kraft and soda. Of these, the Kraft and sulphite processes are most common (Biermann, 1996).

Wood pulp fibres are hollow tubes having normal average diameter of 15-30 µm and length of 1-3 mm. There is a extensive variability around these averages even within one species and like all lignocelluloses material tend to swell in water. Generally, the wood fibres composites are made up of spirally wound fibrils of cellulose (Derakhshandeh et al., 2011).

Gathering all the information about biomass, its benefits, composition of wood and extraction of them and also the effect of water on it could be used for this work as a resource to discuss and analyze the results of the experiments which were carried out during the study. These results are linked to the information summarized in this chapter and the next chapter, and will be discussed and evaluated in the following chapters.

CHAPTER 3

Literature Survey (Multiphase system mixing)

3.1 Introduction

Mixing is a process that increases the homogeneity of a system or more elaborately, it is a level of equilibrium at which all particles species are distributed homogenously through the media with respect to concentration gradient. Generally, mixing processes are classified according to the type of the process materials such as solid-liquid, gas-liquid, immiscible liquid-liquid and also blending viscous liquid (Hosseini, Patel et al., 2010). Mixing plays an important role in a great range of industries such as: biotechnology, food, petrochemicals, polymer processing, drinking water and wastewater treatment, mineral processing, pulp and paper, paints and automotive finishes, fine chemicals, agrichemicals and pharmaceuticals (Paul, Atiemo-Obeng et al., 2004).

In the solid-liquid mixing process, the key objective is to achieve uniform distribution of solid throughout the mixing vessel and in the case of chemical reactor to develop maximum surface area of the solid available for mass transfer. The impeller type and speed should be selected to satisfy this objective. Also the just suspended speed, N_{js}, which presents the complete off-bottom suspension conditions, should be determined (Ayranci and Kresta, 2011).

In this chapter, literature review of multiphase solid-liquid and gas-solid-liquid system processes, minimum impeller speed for just off-bottom suspension and its measurements techniques, mixing of pulp suspension and its rheology are discussed.

3.2 Multiphase Processes

In general, two-third of industrial processes include mixing of at least two material phases through the reaction itself happens in just one of the phases in most of these processes (Atherton, Houson et al., 2011).

3.2.1 Solid-Liquid Mixing

Typically the solid phase is denser than the liquid phase. A very important aspect of mixing is to ensure enough mass transfer and reaction rate in liquid-solid system. Correct agitation of the system is necessary to maintaining the solids both suspended and well dispersed. The just suspended impeller speed, N_{js}, is defined later as the minimum impeller speed at which all solids are lifted from the bottom of the vessel. This is an important parameter and has to be determined experimentally for liquid-solid systems. It is also important in the gas-solid-liquid system (Atherton, Houson et al., 2011).

Practically in all types of operation in stirred tank reactors, the solid phase should be dispersed throughout the fluid volume; transferring of mechanical energy from the agitator to kinetic energy of the liquid and particles cause dispersion. Many factors affect the dispersion of the solids. These include the physical properties of solid (particle size, d_p, particle size distribution and solid density ρ_s) and the liquid (μ, ρ) and also the mechanical design of the tank (T; C/T, D/T, impeller type, etc), as well as the operating parameters (impeller speed, power input, liquid height, solid concentration and solids volume fraction) (Stitt and Simmons, 2011). Usually, the suspension of a dense solid ($\rho_s > \rho$) requires high impeller speed. When the impeller speed is increased, the particles would leave the bottom of the vessel and stay suspended in the liquid (Stitt and Simmons, 2011). For solid suspension, the pitched blade impellers with diameters of $D< T/ 2.5$, placed near the vessel base ($C < T/4$) are very suitable. On the other hand, generally to disperse gas through a stirred vessel it is recommended to have the impeller clearance of T/6 (Hemrajani and Tatterson, 2004), Therefore, in this study the impeller was placed at T/6 from the bottom of stirred tank.

Generally, in solid-liquid mixing, solid particles tend to settle on the bottom of vessel or to float on surface of liquid. Settling solid particles have a higher density than the liquid and that is why they settle without agitation. On the other hand, solids that float without agitation are less dense than the liquid, and typically such solids are more difficult to wet than dense solids with trapped gas. Frequently, solid-liquid mixing operations take place in the presence of gas bubbles forming gassed suspensions. In this case, the gas bubbles may be introduced directly, as in solid catalysed hydrogenation reactions, entrained accidentally or deliberately from the headspace, or appear as in an evaporative crystallisation or as a gaseous reaction product (Atiemo-Obeng et al., 2004).

3.2.1.1 Hydrodynamics of solid suspension and distribution

Generally, there are three levels for the degree of solids suspension in agitated vessels. It is illustrated in figure 2 (Atiemo-Obeng et al., 2004).

1. On-bottom motion
2. Complete off-bottom suspension
3. Uniform suspension

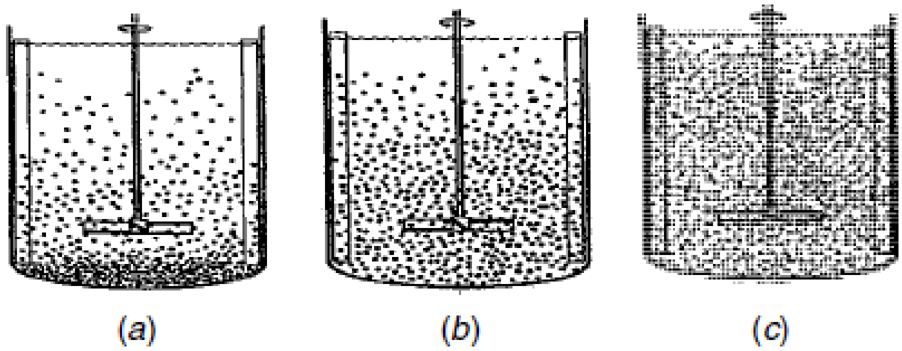


Figure 2 Degree of suspension, (a) Partial suspension (b) Complete suspension (c) Uniform suspension (Atiemo-Obeng et al., 2004).

In mechanically agitated vessels, the minimum required agitation speed for the just suspended state is the minimum agitation conditions at which all particles reach complete suspension, N_{js}. This has been the subject of many theoretical and experimental analyses (Atiemo-Obeng et al., 2004).

For the just suspended speed in stirred vessels, there are some other factors which should be considered while hydrodynamics of the solid suspension is analysed: (Atiemo-Obeng et al., 2004).

- The effect of fluid viscosity
- The effect of solid loading
- The effect of fluid particle size
- The effect of vessel and impeller geometry and scale

3.2.1.2 Impeller flow pattern

As described in chapter 4 (Experimental procedures), there are three different types of impellers used in the experiments. Depending on the type of impeller used for this study, different flow patterns were observed.

Radial flow: as it can be seen in fig 3, using Rushton turbine impeller formed four flow loops, two above and two below the impeller. Usually, this type of impeller is recommended for single-phase operation as well as gas dispersion through the stirred reactor (Stitt and Simmons, 2011).

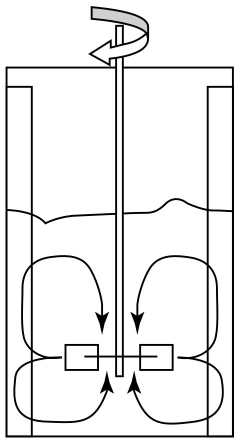


Figure 3 Radial flow pattern of Rushton turbine impeller (Stitt and Simmons, 2011).

Axial flow: as an up-pumping Pitched blade (PBT) impeller and helical ribbon screw impeller with top-to-bottom turnovers was used in experiments, just two flow loops were formed with the flow pumping through the impeller plane near the shaft. This type of axial flow can be seen in figure 3 (Stitt and Simmons, 2011).

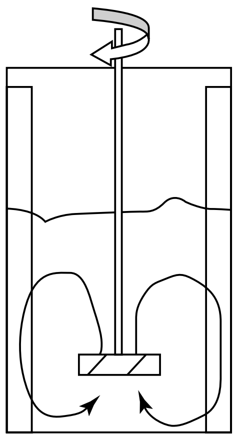


Figure 4 Axial flow pattern of pitched blade and helical ribbon screw impeller (Stitt and Simmons, 2011).

3.2.2 Suspension of Solid with Gas Dispersion

For many industrial processes, agitated three-phase systems (gas dispersion with solid suspended in liquid) are required. In these cases, the most important issue is the choice of agitator type and scale of the process but the following should also be considered: (i) The ability of impeller to suspend solids instantaneously and disperse gas without flooding, (ii) gas-liquid mass transfer performance in the presence of solids, which is related to, the power input from the agitator and specific energy dissipation rate. (iii) Gassed power characteristics of the type (Nienow and Bujalski, 2002).

In three-phase (gas-liquid-solid) systems in stirred vessel there is a particular mixing challenge. The presence of gas tends to disturb the liquid flow patterns established by the rotating impellers. Occasionally, the gas is entrapped by solid agglomerates increasing their tendency to float (Atiemo-Obeng et al., 2004).

3.2.3 Industrial Mixing of Pulp Suspension

In the pulp and paper industry, the problem of designing and scaling-up agitated stock chests has been investigated mainly by semi empirical methods. Yackel (Yackel, 1990) has summarized a very common design method. This method is based on matching the momentum flux produced with an impeller, which needed to provide complete motion in the chest. Using Yackel's definition, "complete motion" happened when there is a movement over the entire top surface of the mixing vessel (Ford et al., 2006).

Ein-Mozaffari et al. (Ein-Mozaffari et al., 2003) worked on the dynamics of pulp agitation using a 1:11 scale-model Plexiglas chest equipped with a side entering impeller. They found that even when complete surface motion was achieved, significant recirculation, channeling and stagnation occurred below the suspension surface. In numerous cases, the suspension volume involved in active mixing was only 20 to 40% of that in the chest. The unfavorable flows responsible for this occur due to the complex rheology of the pulp suspensions (Ford et al., 2006).

Pulp suspensions are non-Newtonian fluids and they frequently form continuous fibre networks, which possess structure and strength because of interaction between neighboring fibres. To keep such suspension in motion, the shear stresses forced on the suspension must be greater than the network strength, which is measured as the suspension yield stress. Frequently pulp suspensions are treated as plastic materials; they show slight deformation up to the yield stress and only flow once the yield stress is exceeded. Also fiber suspensions show nonlinear viscoplastic properties, such as shear thinning, while, after yield-point, pulp suspensions display complex rheology that is not well characterized (Ford et al., 2006).

3.2.3.1 Pulp Suspension Rheology

In industrial mixing processes, many fluids display complex rheological behavior. Special challenges are encountered when rheological properties change during processing or when mixing yield stress fluids producing caverns around impellers. To help understand suspension mixing behavior, computational fluid dynamics (CFD) has been used, along with range of experimental techniques. Though, difficulty determining suspension rheology increases the difficulty of CFD implementation and the uncertainty in their predictions. A difficult task is to achieve exact and adequate experimental data from the dense pulp suspensions to validate computational results (Gomez, Derakhshandeh et al., 2010).

Generally, pulp suspensions have unique rheology. They are multiphase suspensions, non- Newtonian and may possess a yield stress which can affect their flow behavior and frequently suspension local mass concentration changes during pulp production (Bhattacharya, Gomez et al., 2010) (Ein-Mozaffari, Bennington et al., 2007) (Gomez, Derakhshandeh et al., 2010). This frequently leads channelling (bypassing) and dead zones (stagnant regions or flows considerably slower than the bulk of the suspension), which reduce mixing quality (Bhattacharya, Gomez et al. 2010) (Ein-Mozaffari, Bennington et al., 2007).

Non-ideal flows involve short circuiting (where a portion of the feed flows directly to the exit without entering the mixing zone) and recirculation (where a portion of the stock recirculates within the mixing zone). Unfavorable flows rise from interactions between the circulation patterns generated by the impeller and the suspension flow within the vessel and are also affected by the chest geometry. Similar results have been reported for industrial chests (Ein-Mozaffari, Bennington et al., 2007).

Several observations could be described the cavern which is formed around the impeller (the region of actively mixed flow) approached the pulp outlet, the fraction of flow short-circuiting the mixing zone approached zero. However, yield stress alone could not fully account for the such dynamic behavior (Ein-Mozaffari, Bennington et al., 2007).

3.2.3.2 Shear viscosity

Generally, few studies have been dedicated to measure the viscosity of pulp suspension, though; there have been a substantial number for the simple case of synthetic (glass, plastic) fibres on uniform size and shape (Derakhshandeh et al., 2011).

Blakeney (Blakeney, 1966) has evaluate the effect of fibre concentration on the relative viscosity of suspensions of straight rigid nylon fibres and he found out the viscosity increases with concentration (Derakhshandeh et al., 2011).

Chaouche and Koch (Chaouche and Koch, 2001) have evaluated the effect of shear stress and fibre concentration on the shear-thinning behavior of rigid fibre suspensions. They concluded that the non-Newtonian suspending liquid played a key role in shear-thinning behavior of suspension at high shear rate values (Derakhshandeh et al., 2011).

Chase et al. (1989) has measured the variation of torque versus rotational rate of soft wood and hard wood pulp suspensions to work on the effects of fibre concentration on the viscosity parameter and found out that for both suspensions, viscosities increases linearly with consistency (Derakhshandeh et al., 2011).

3.3 Minimum impeller speed (N_{js})

The theoretical correlation for N_{js} indicates that N_{js} in presence of gas in the system is higher than for the un-gassed systems. Chapman et al. (1983) has found that when the gas flow rate is increased, considerable increases in N_{js} is needed to reach a complete suspension of the solids. Also, the impeller speed needed for the just suspended state is always greater than that needed for a complete dispersion of the gas bubbles. At volume of gas flow rate less than 0.75 $m^3.min^{-1}$, 45^o pitched blade impeller is more effective than disk or Rushton turbine for solid suspension (Brown et al., 2004).

3.3.1 Minimum impeller speed (N_{js}) measurements

Generally, N_{js} is known as the minimum agitator speed at which all solids in the vessel are suspended and it is one of the most favorable operating point for mass transfer in the vessel (Paul, Atiemo-Obeng et al., 2004). At minimum impeller speed, all the particles are in motion and there are no particles settled on the tank base for more than 1-2 seconds. Usually, this speed is called "just off-bottom suspension" speed (Zhu and Wu, 2002) or "just complete suspension" speed (Ghionzoli, Bujalski et al., 2007).

Below this speed, the total solid liquid interfacial surface area is not efficiently or entirely used, and also above this, the solid-liquid mass transfer rate rises gradually with agitation power. Consequently, it is very important to be able to determine the N_{js} at which the just suspended state is attained by particles (Armenante and Nagamine, 1998).

In general, there are three main techniques to measure the N_{js} as follows;

1. Visual Techniques (Brown et al., 2004)
2. Ultrasonic Doppler Flow meter Probe (Brown et al., 2004)
3. Conductivity Probe (Brown et al., 2004)

In this work visual observation method has used to measure the minimum impeller speed in all experiments using different types of impellers. These observations are discussed in the in details in the chapter 5 and 6.

Visual Techniques

Making visual observations through the base of the vessel is the most common way of estimating N_{js}. In this case, the vessel should be equipped with a transparent base. Many researchers have defined the just suspended state, using different criteria. These criterion can be classified as follows (Brown et al., 2004);

1. No solids remain stationary on the vessel base for more than 1 or 2 seconds.
2. No solids remain stationary on the vessel base for more than 2 to 4 seconds.
3. No solids remain on the vessel base for more than 1 to 2 seconds.

So it is very important to select an N_{js} criteria related to the process under investigation, and also one, which is reliable with any other data, which are being referenced (Brown et al., 2004).

To measure N_{js} by visual technique, an operator can either lay on her/his back under the vessel or even observe a reflection of the base in a mirror. It should be considered that to be sure of the results, a large enough segment of the vessel base needs to be observed. Usually, many repeats gradually increasing the impeller speed and monitoring the vessel base for stagnant particles should be made. Before checking to see if the chosen "just suspension" criterion has been reached, it should be allowed the sufficient time for steady state to be reached. If not, the impeller speed should be increased and the observation repeated (Brown et al., 2004).

CHAPTER 4

Experimental Procedures

4.1 Introduction

In chapter 2, it was discussed that nowadays it is necessary to replace fossil fuels and other non-renewable sources with biomass such as waste wood to produce chemicals and bio fuels.

The whole concept of this research is related to production of certain chemicals and pharmaceuticals such as acetic acid, furfural, itaconic acid, lactic acid, succinic acid, hydrogen, methanol and vanillin (MacKay, Cole et al., 2009) from woody biomasses. In order to produce such chemicals, it is necessary to study the mixing in two-phase system (water and wood) and in three-phase system (water, wood and air). The main purpose of this research is to analyze the mixing processes in terms of power consumption and specific energy dissipation rate and to determine the torque as a function of rotational speed, fluid properties and impeller geometry, which can be used for scale up.

In this chapter, different types of impeller are examined in mixing of water as continuous phase and wood pellets (Brites wood pellets) as dispersed phase, with or/and without gas flow (air) as gas phase. The following sections describe the experiments, which have been carried out during the research.

4.2 Equipment and Materials

Stirred solid-liquid (two-phase) and gas-solid-liquid (three-phase) systems have been frequently investigated in the process industries and impeller design for multiple phase operations is a stimulating and industrially applicable task. Usually, the information of the extent of the solid mixing is necessary for the determination of overall rates of mass and heat transfer and also reaction rate therefore it is important in the design and scale up of solid suspension mixing equipment. Generally, it is obvious that better understanding of the solid dispersion is dependent on the rational design and scale-up of two phase (solid-liquid) and three phase (gas-solid-liquid) stirred tank reactors. Selection of appropriate impeller is of vital importance, because the impeller choice provides good mixing under changing hydrodynamic during the reaction in stirred tank (Dohi, Takahashi et al., 2004).

4.2.1 Stirred reactor

For this research, a cylindrical fully baffled lab stirred vessel of T= 19cm internal diameter and L= 30 cm height which is shown in figure 6 has been used in the experiments with Rushton turbine and pitched blade impeller. The stirred vessel have flat bottom with four 1.8 cm-width baffles (figure 5).

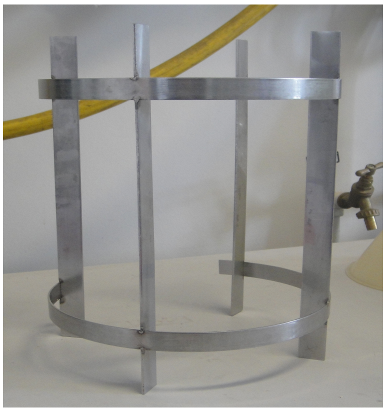


Figure 5 The four baffles of 1.8 cm-width used in experiments.

This glass reactor with a flat bottom and bottom outlet consisting of the glass vessel has a volume of seven litres and was agitated by three different types of impellers; a six-bladed disk turbine (Rushton turbine) impeller of D=7.5 cm, a six-bladed pitched impeller of D=7cm or a helical ribbon impeller of D=6.5 cm. It is known that for equal power input, multiple impellers are less efficient for suspension than a single impeller (Chapman et al., 1983). That is the main reason of selecting Rushton Turbine, pitched blade and helical screw impellers for this study.

Figure 6 The laboratory stirred vessel used in this study.

During all the experiments in the glass vessel, the volume of the solid-liquid mixture was constant and equal to 5.5 L and the temperature was also kept constant at room temperature. Torque and impeller speed was monitored and recorded with a controller (Fig 7) connected to a motor and a computer.

Figure 7 The controller and monitor of the stirred reactor.

Torque and impeller speed were measured to calculate power consumption and energy dissipation rate. However, when torque was measured strong fluctuations were observed. So in the calculated power consumptions and energy dissipation rates, the average torque has been used for each impeller speed. These calculations and their results are presented in details in chapter 5 (Impeller Performance Results).

The helical screw impeller was examined in a beaker of T=8.5cm and volume= 0.623 L shown (Figure 8).

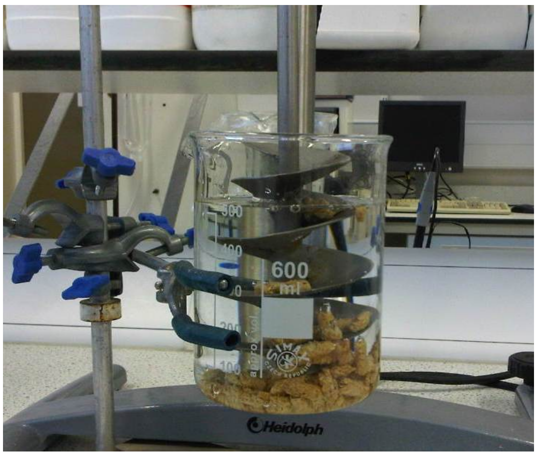


Figure 8 Stirred vessel (beaker) fitted with helical screw impeller.

4.2.2 Wood pellet

The saw dust can be converted in a pellet in order to use, store and transport easily. The wood pellets, which are used in the experiments, are supplied by Brites. Brites wood pellets are produced using renewable energy and raw materials sourced from limited, sustainably managed forests by Balcas in Northern Ireland and Scotland (Brites, 2012).

Brites wood pellets (figure 9) are from wood residue and are obtained as a by-product of the saw milling process. The main component of these pellets is either pine or spruce (Brites, 2012). All Brites wood pellets' properties are summarized in Table 1 (Brites, 2012).

Figure 9 Brites wood pellets (Brites, 2012).

Table 1 Properties of Brites wood pellets (Brites, 2012).

Origin	Woody Biomass
Traded Form	Pellets
Size	Diameter: 6mm ±1.0mm Length (L): 3.15 ≤ L ≤ 40mm
Bulk Density	≥ 600 kg/m3
Calorific Value	≥ 16.5 MJ/kg
Moisture	≤ 10%
Fines Material *(< 3.15mm)*	≤ 1.0 %
Mechanical Durability	≥ 97.5 %
Ash Content	≤ 0.7%
Chlorine	≤ 0.02%
Sulphur	≤ 0.05%
Nitrogen Content	≤ 0.3%
Copper Content	≤ 10 mg/kg
Chrome Content	≤ 10 mg/kg
Arsenic Content	≤ 1 mg/kg
Cadmium	≤ 0.5 mg/kg
Mercury Content	≤ 0.1 mg/kg
Lead Content	≤ 10 mg/kg
Nickel Content	≤ 10 mg/kg
Zinc Content	≤ 100 mg/kg
Additives	≤2% of dry bases (natural)
Bark	None
Ash Softening Temp.	≥ 1200 °C

4.2.3 Air flow

In the experiments of using Rushton Turbine and Pitched blade impellers, the air (gas phase) was sparged from a pipe located at the corner of the vessel. The pipe had the diameter of 3 mm and length of 27cm and was entered from the top of the stirred vessel as can be seen in the following figure. The gas flow rate was varied from 0 to 20 L.min^{-1} (0-10-20 L.min^{-1}).

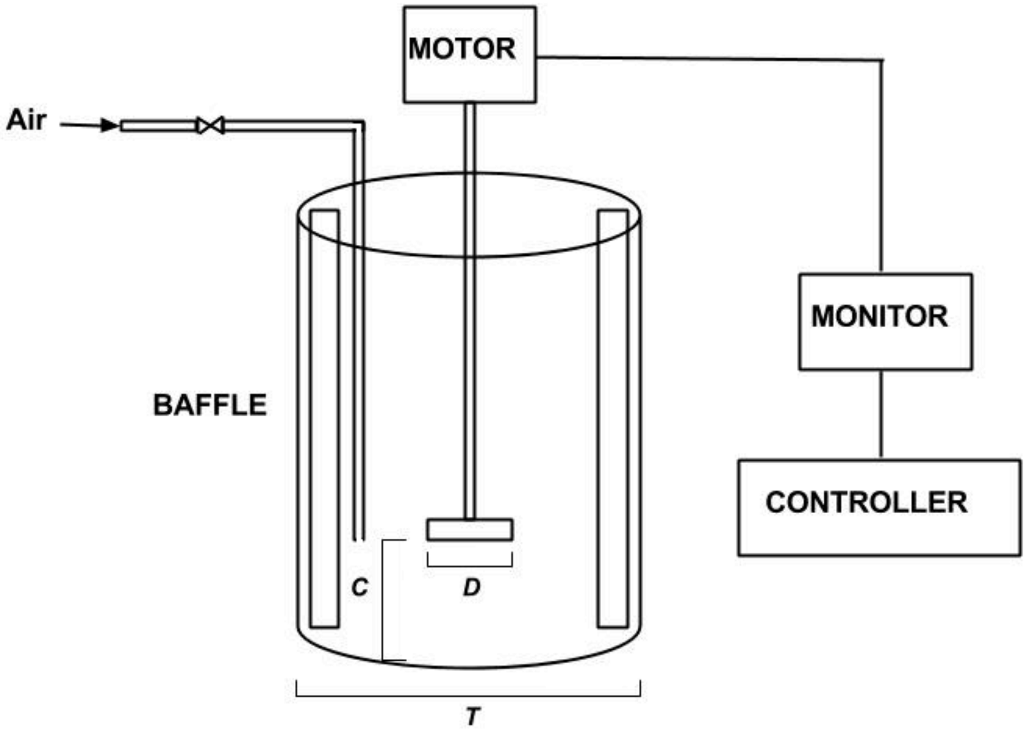


Figure 10 Gas sparging throughout the stirred vessel.

In the experiments where helical screw impeller was used, it was not possible to sparge with the air, so those experiments were carried out without airflow.

4.3 Preliminary Experiments (1)

Initially floatation of wood pellets on water due to the density differences was considered to be a major problem. But after few preliminary experiments in which, the wood pellets were put in water, it was found out that this type of wood pellet do not float on water. They sink in water and remain at the bottom of the stirred vessel without agitation (Figure 11).

Figure 11 Brites wood pellets sink in water without agitation.

As shown in table 1, the bulk density of Brites wood pellets is ≥ 600 kg.m^{-3}, which is less than 1000 kg.m^{-3} (density of water) therefore pellets should float on water. But from the very first second of putting it in water, it sinks. Clearly, the density reported by manufacturer was incorrect and it was essential to determine the exact density of Brites wood pellets.

4.3.1 Determination of density

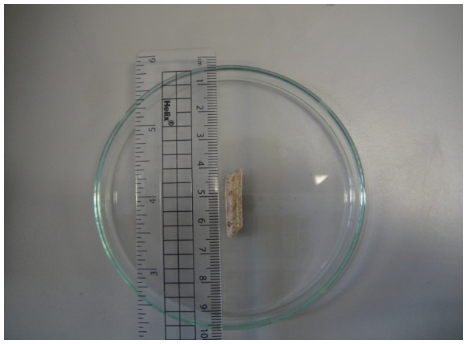
In this study, the shapes of the wood pellets were cylindrical In order to know the volume of pellets, it is common to add a specific amount of water in a cylinder, and record the volume. Then solids should be placed into the cylinder, read the level of the water in the cylinder so, the change in the water level represents the volume of the solid. Based on the above measurements in which water is rapidly absorbed by pellets, it was found that density of Brites wood pellets was approximately 1400 kg.m^{-3}. The measured density of Brites wood pellets was reasonable as they sink in water.

4.4 Preliminary experiment (2)

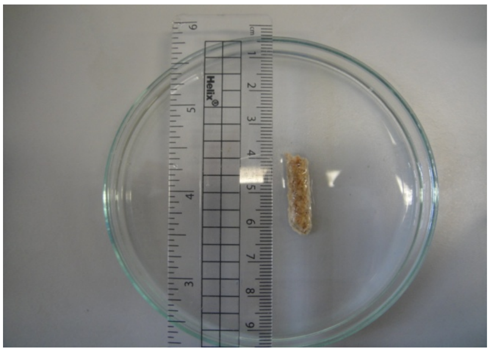
In lignocelluloses, commonly lignin is presented as a highly cross-linked aromatic polymer built from phenylpropanoid units it can act as “glue”, that binds cellulose and hemicelluloses, imparting rigidity and microbial resistance to the cell wall (Fu, Mazza et al., 2010). Therefore, there is no need for additives in manufacturing of Brites wood pellets. In such a case, it was essential to investigate the kinetics of disintegration of a single pellet.

The following sequence of figures shows a wood pellet in a petri dish. It is in contact with water for forty minutes and it is clear that from the moment the wood pellet comes in contact with water, it started to expand and gradually disintegrated into small wood particles.

t=0



t=0 (without water)

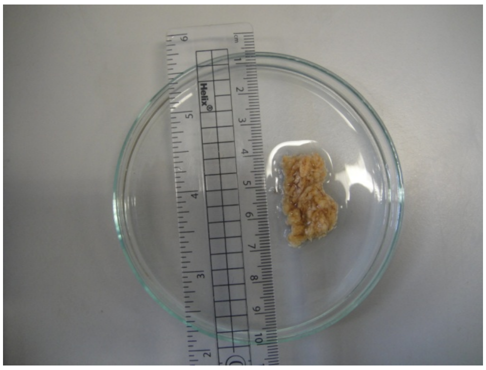
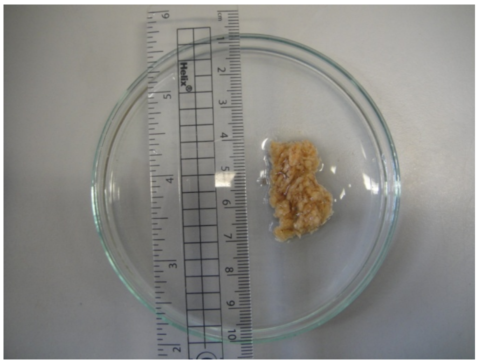


t=0 min (water is added)

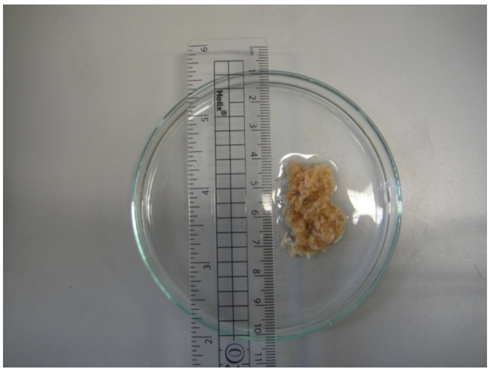
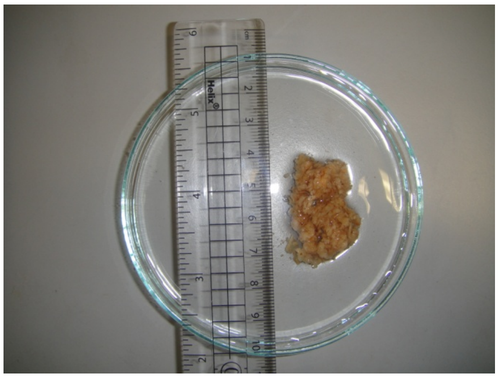
t= 1min

t=2 min

t= 3min

t= 4 min t= 5min

t= 20 min t= 40 min

Figure 12 Wood pellets fast disintegrating in water.

As can be seen in Figure 12, after five minutes under static conditions, wood pellet is completely disintegrated and there are no changes in morphology after five minutes (At t=20 min and t=40 min). This means that five minute is the maximum time for this type of wood pellet (Brites wood pellets) to disintegrate.

4.4.1 Morphology of wood fibres

As, fast disintegration of wood pellets in water were observed, it was necessary to know more about morphology of wood fibre.

4.4.1.1 Particle size measurements

The size distribution is a necessary to evaluate the behavior of granular material in fluid (Plater, 1993). To size the wood particles, representative samples were taken from the bulk and analyzed using Malvern MasterSizer 2000. The results are described later in next chapter.

Standard Operating Procedure (SOP) of Malvern MasterSizer 2000 is as follow:

1. Switch MasterSizer on.

2 Fill the liquid circulation system with water and switch the pump on. Wait for approximately 10 -15 min, until temperature of the system stabilises and the air bubbles disappear.

3. Set the MasterSizer to automatic mode

4. Slowly add suspension of particles (no more than 1ml per time) and observed the beam obscuration on the computer screen.

5. Start the measurement when obscuration is in the required range (as display on the computer).

6 Run each sample for 3-5 min in fully automatic mode.

7 Once the measurement is completed (distributions are displayed on the screen) save the file and discharge the suspension from the cell.

8. Wash the cell with distilled water, repeat the procedure two more times for the same system , compare the results.

4.4.2 Rheological measurement

Viscosity provides a very important insight into the structural and dynamic properties of the suspension (Ziemann et al., 1994). So, after determining the density of Brites wood pellets and observing the morphology of wood fibres, it was necessary to measure the viscosity.

The rheological measurements for all the fluids were carried out in a TA AR 1000 (TA instrument) vane and basket, equipped with a 6-blade Rushton turbine impeller with 30 mm diameter.

Three samples of 5,10 and 15 wt% wood pellet concentration were prepared after five minutes of mixing with impeller speed of 400 min^{-1}, then they were put in the viscometer. The results of this measurement are discussed in next chapter.

4.5 Experiments

The effect of the type of impellers on the concentration distribution of composite pellets in a stirred reactor was investigated.

4.5.1 Operating conditions

As shown in later, experiments were conducted using Rushton Turbine, pitched blade impeller and helical screw impeller. In all experiments, liquid phase (tap water), solid phase (wood pellets) were mixed with or without gas phase (air) for five minutes. In all cases, the solid loading was varied from 5 to 15wt % (5-10-15wt%) and for each wood concentration, the impellers speed was increased from 200 rpm to 1000 rpm (for the Rushton Turbine and pitched blade impeller) and 35 rpm to 185 rpm (for the helical screw impeller). In experiments in which air was used, the flow rate of the air was 10 or 20 $lit.min^{-1}$.

As, Zwietering (1958) reported, for paddles, propellers and disc turbine, N_{js} (minimum impeller speed) would become lower when the impeller off-bottom clearance to tank diameter ratio (C/T) was decreased. Also Zwietering found that for six-blade disc turbine, the minimum impeller speed of complete suspension was independent of C/T for $1/7<C/T<1/2$. Though, Chapman et al. (1983) and Nienow (1968) disagree with these results. They have found that the impeller clearance has an important effect on N_{js} for disc turbine. Also, they have reported that at high impeller clearance, large recirculation flows below and above the impeller are present and is called “double-eight” flow regime. But the lower recirculation flow is absent at low clearance, and this case is called “single-eight” flow regime (Armenante and Nagamine, 1998).

In the latter case, N_{js} - N_{jsg} and also the power dissipated at constant impeller speed in the stirred vessel are lower. Gray (1987) has reported that the power consumed at N_{js} on the impeller clearance was strongly dependent on the flow pattern. These results show that N_{js} and P_{js} are highly dependent on the type of hydrodynamic regime in which the impeller operates (Armenante and Nagamine, 1998).

Using all reported results by Nienow, Chapman et al., Gray helped to choose the minimum possible impeller clearance (C/T=1/6) of 3.8cm for six-blade Rushton turbine impeller.

Generally, it is considered that the distance between the impeller and the tank base plays an important role for solid suspension. In this study, the impeller clearance, C, was measured from the bottom of the impeller to the tank bottom. To improve the off-bottom suspension, the impeller clearance would be rather small (Dohi, Takahashi et al., 2004).

4.5.1.1 Rushton turbine impeller

Figure 13 shows a six-bladed Rushton turbine impeller of D= 7.5cm which has been used in the experiments and as the following table shows, the operating condition was exactly same when pitched blade impeller was used.

Figure 13 A six-bladed Rushton turbine impeller.

Table 2 Operating conditions of the experiments using a Rushton turbine impeller.

Wood pellets mass (g)	1) 5 wt % = 265g 2) 10 wt % = 530g 3) 15 wt % = 794g
Water mass (g)	1) 95 wt % = 5031g 2) 90 wt % = 4766g 3) 85 wt % = 4502g
Impeller speed (min^{-1})	200-400-600-800-1000
Conditioning time (min)	5
Clearance (cm)	3.8
Temperature (°C)	23
Liquid dept in tank (cm)	=H=D=19
Air flow rate	0-10-20 $L.min^{-1}$

The main parameter, which was measured, was the torque. The following table shows the measured torque when the Rushton turbine impeller was used.

Table 3 Measured torques using Rushton turbine impeller.

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	5	200	0	0.079
10	5	400	0	0.14
15	5	600	0	0.23
20	5	800	0	0.35
25	5	1000	0	0.47
5	5	200	10	0.075
10	5	400	10	0.14
15	5	600	10	0.22
5	5	200	20	0.074
10	5	400	20	0.15
15	5	600	20	0.26

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	10	200	0	0.094
10	10	400	0	0.14
15	10	600	0	0.22
20	10	800	0	0.33
25	10	1000	0	0.46
5	10	200	10	0.075
10	10	400	10	0.13
15	10	600	10	0.21
20	10	800	10	0.27
25	10	1000	10	0.34
5	10	200	20	0.076
10	10	400	20	0.13
15	10	600	20	0.22
20	10	800	20	0.32
25	10	1000	20	0.35

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	15	200	0	0.09
10	15	400	0	0.15
15	15	600	0	0.23
20	15	800	0	0.36
25	15	1000	0	0.47
5	15	200	10	0.08
10	15	400	10	0.13
15	15	600	10	0.2
20	15	800	10	0.23
25	15	1000	10	0.26
5	15	200	20	0.09

10	15	400	20	0.14
15	15	600	20	0.19
20	15	800	20	0.2
25	15	1000	20	0.26

Figure 14 show the completed experiments using Rushton turbine impeller without airflow, which is followed, by figure 15 showing the experiments of using same impeller with airflow.

(a)

(b)

(c)

Figure 14 Finished experiments of using Rushton turbine impeller without air flow, (a) Experiment of 5wt% solid, (b) experiment of 10 wt% solid and (c) experiment of 15 wt% solid.

(a)

(b)

(c)

Figure 15 Finished experiments of using Rushton turbine impeller with air flow of 10L.min^{-1}, (a) Experiment of 5wt% solid, (b) experiment of 10 wt% solid and (c) experiment of 15 wt% solid.

4.5.1.2 Pitched blade impeller

As can be seen in following figure a 45° pitched blade of D= 7cm is used in this part of the research with the operating conditions that are summarized in table 4.

Figure 16 The pitched blade impeller used in the experiments.

Table 4 Operating conditions of the experiments using pitched blade impeller.

Wood pellets mass (g)	4) 5 wt % = 265g 5) 10 wt % = 530g 6) 15 wt % = 794g
Water mass (g)	4) 95 wt % = 5031g 5) 90 wt % = 4766g 6) 85 wt % = 4502g
Impeller speed (min^{-1})	200-400-600-800-1000
Conditioning time (min)	5
Clearance (cm)	3.8
Temperature (°C)	23
Liquid dept in tank (cm)	H=D=19
Air flow rate	0-10-20 $L.min^{-1}$

As in the experiments with Rushton turbine, it was essential to measure the torque at increasing impeller speed. All the torques are summarized in following table.

Table 5 Measured torques of using Pitched blade impeller.

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	5	200	0	0.08
10	5	400	0	0.11
15	5	600	0	0.17
20	5	800	0	0.24
25	5	1000	0	0.32
5	5	200	10	0.072
10	5	400	10	0.11
15	5	600	10	0.16
20	5	800	10	0.22
5	5	200	20	0.07
10	5	400	20	0.11
15	5	600	20	0.16
20	5	800	20	0.23

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	10	200	0	0.08
10	10	400	0	0.13
15	10	600	0	0.18
20	10	800	0	0.26
25	10	1000	0	0.34
5	10	200	10	0.08
10	10	400	10	0.11
15	10	600	10	0.17
20	10	800	10	0.24
25	10	1000	10	0.32
5	10	200	20	0.069
10	10	400	20	0.11
15	10	600	20	0.17
20	10	800	20	0.24
25	10	1000	20	0.3

Time (min)	Solid concentration (wt %)	Impeller speed (min^{-1})	Air flow rate ($L.min^{-1}$)	Average torque (Nm)
5	15	200	0	0.16
10	15	400	0	0.17
15	15	600	0	0.23
20	15	800	0	0.3
25	15	1000	0	0.37
5	15	200	10	0.07
10	15	400	10	0.12
15	15	600	10	0.15

20	15	800	10	0.19
25	15	1000	10	0.23
5	15	200	20	0.07
10	15	400	20	0.12
15	15	600	20	0.15
20	15	800	20	0.18
25	15	1000	20	0.23

4.5.1.3 Helical screw impeller

The helical screw impeller of D= 6.5 used in the experiments is shown in figure 17. Due to the difficulties of ordering or manufacturing a helical screw suitable for the stirred vessel described above, it was decided to carry out this set of experiments in a beaker suitable for the existing helical ribbon impeller. Following figure and table show the characteristic dimensions of the helical ribbon mixer used in this study.

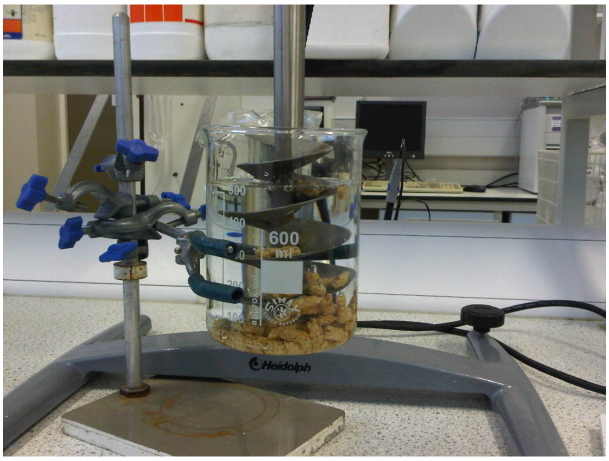


Figure 17 Helical screw impeller used in the experiments.

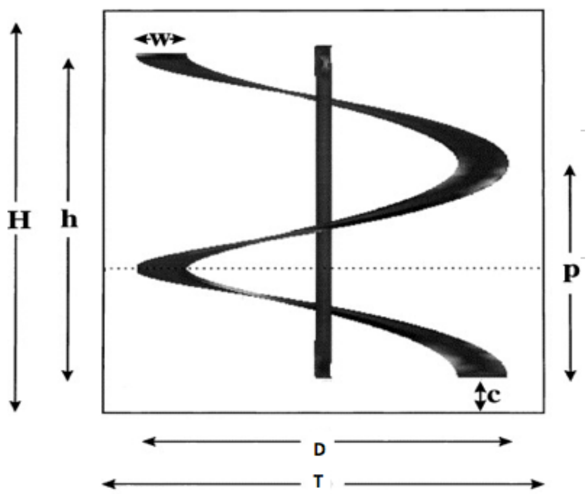


Figure 18 Sketch of the helical ribbon impeller.

Table 6 Characteristics dimensions of the used helical ribbon mixer.

T (cm)	D (cm)	w (cm)	p (cm)	H (cm)	h (cm)	H/T	T/D	w/D	p/D
8.5	6.5	2.5	2.8	8.5	9	1.00	1.3	0.38	0.43

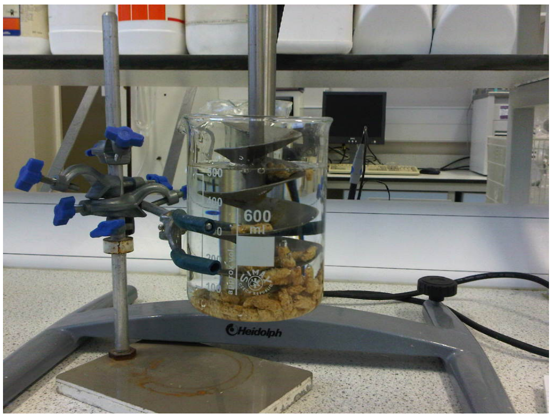
As the vessel used for helical ribbon was different with the one, which was used for Rushton turbine and pitched blade impeller, it was not possible to conduct the experiments with airflow. So the following table shows the operating conditions of the experiments using helical ribbon without air flow.

Table 7 Operating conditions of the experiments using helical ribbon impeller.

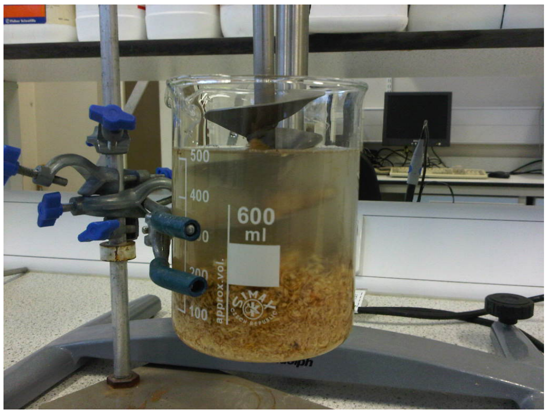
Wood pellets mass (g)	1) 5 wt % = 25.85g 2) 10 wt % = 51.717g 3) 15 wt % = 77.57g
Water mass (g)	1) 95 wt % = 491.31g 2) 90 wt % = 466g 3) 85 wt % = 439.59g
Impeller speed (min^{-1})	35-65-95-125-155-185
Conditioning time (min)	5
Clearance (cm)	0.5
Temperature (°C)	23
Liquid dept in tank (cm)	H=9

1. 5wt % wood pellets

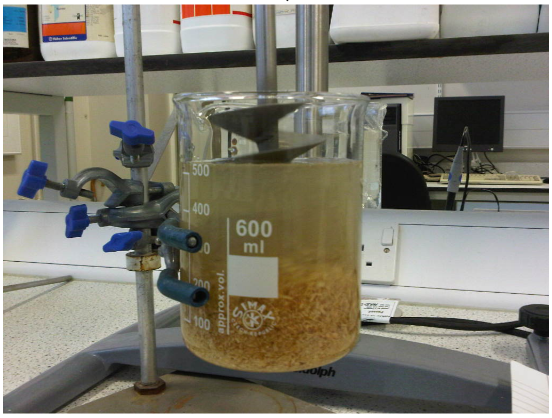
All experiments with the helical ribbon impeller are summarized for each impeller speed with conditioning time of five minutes below. The first figure shows pellets at time zero at which impeller speed was zero, then impeller speed of 35min^{-1} follows by increasing up to 65, 95, 125, 155 and 185 min^{-1} every five minutes. The last figure shows the stirred vessel after the experiment when the impeller was stopped.



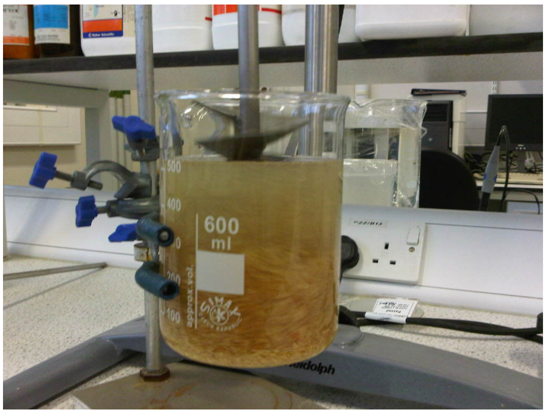
t=0 min, N= 0 min^{-1}



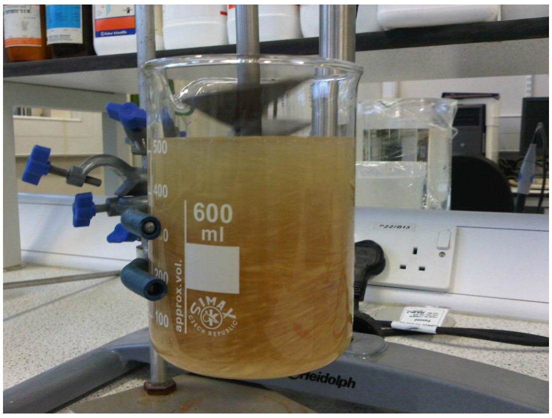
t=5 min, N=35 min^{-1}



t= 10min, N= 65 min^{-1}



t=15min, N= 95 min^{-1}



t= 20 min, N= 125 min^{-1}

t= 25 min, N= 155 min^{-1}

t= 30min, N= 185 min^{-1}

t= 35 min, N= 0 min^{-1}

Figure 19 Time sequence of using helical ribbon screw impeller (5 wt% solid concentration).

It is clear that when impeller has stopped, immediate phase separation occurred. The measured average torque of each impeller speed and wood pellet concentrations are summarized in the table below.

Table 8 Measured torques of using helical ribbon impeller.

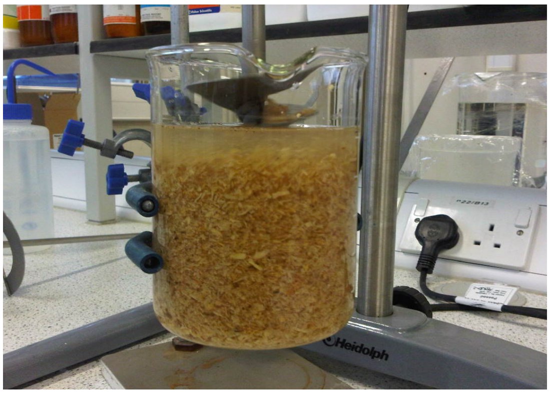
Time (min)	Impeller speed (min^{-1})	Solid concentration (wt %)	Average torque (Nm)
5	35	5	0.072
10	65	5	0.083
15	95	5	0.092
20	125	5	0.095
25	155	5	0.096
30	185	5	0.099

2. 10 wt% wood pellets

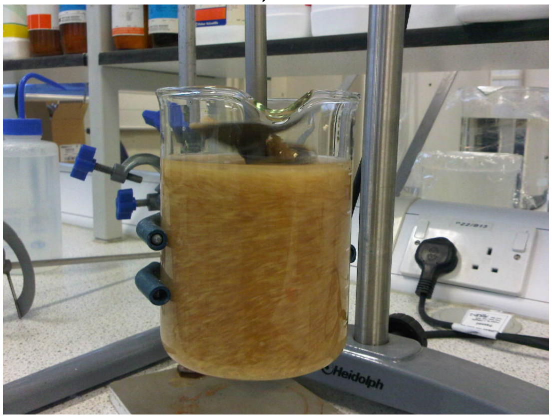
The following figures are the experiments of using helical ribbon impeller with 10 wt% solid concentration (wood pellets). The figures are all in the same order as the experiments with 5 wt%. It starts with impeller speed of equal to zero at t=0 and ends with impeller speed of equal to 185 min^{-1}.

t= 0 min, N= 0 min^{-1}

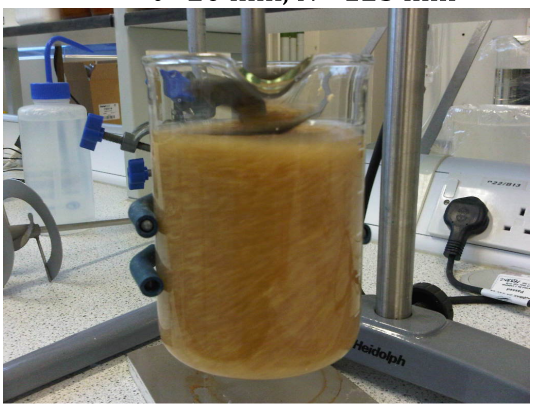
t= 5 min, N= 35 min^{-1}



t= 10 min, N= 65 min^{-1} t= 15 min, N= 95 min^{-1}



t= 20 min, N= 125 min^{-1} t= 25 min, N= 155 min^{-1}



t= 30 min, N= 185 min^{-1}

Figure 20 Time sequence of using helical ribbon screw impeller (10wt% solid concentration).

Following table shows the average measured torque of 10 wt% solid concentrations for each impeller speed.

Table 9 Measured torques of using helical ribbon impeller.

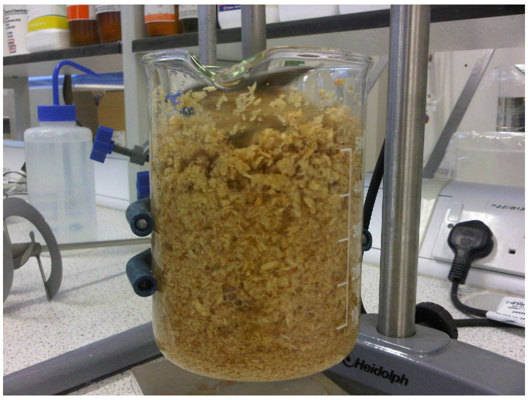
Time (min)	Impeller speed (min^{-1})	Solid concentration (wt %)	Average torque (Nm)
5	35	10	0.065
10	65	10	0.073
15	95	10	0.082
20	125	10	0.086
25	155	10	0.09
30	185	10	0.092

3. 15wt% wood pellets

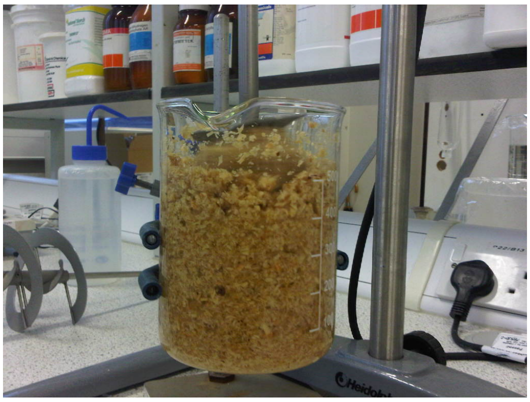
As it can be seen in figure 21, experiments of using helical ribbon impeller have been repeated with 15wt% wood pellet concentration same as the operating conditions of 5 and 10wt% solid concentration.

t= 0 min, N= 0 min^{-1}

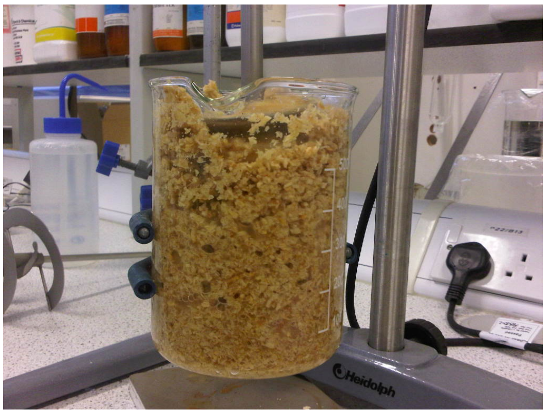
t= 5 min, N= 35 min^{-1}



t= 10 min, N= 65 min^{-1}



t= 15 min, N= 95 min^{-1}



t= 20 min, N= 125 min^{-1}

t= 25 min, N= 155 min^{-1}

t= 30 min, N= 185 min^{-1}

Figure 21 Time sequence of using helical ribbon screw impeller (15wt% solid concentration).

It is obvious in the above figures, 15 wt% of wood pellet concentration exceeds the maximum solid concentration for this study. After five minutes of mixing it is clear that liquid phase (water) cannot be seen and it has totally disappeared in the wood particles. The following table shows the average torque of each impeller speed during the experiment, which is not reliable for any further discussion and conclusion due to including the high solid concentration of 15 wt%.

Table 10 Measured torques of using helical ribbon impeller.

Time (min)	Impeller speed (min^{-1})	Solid concentration (wt %)	Average torque (Nm)
5	35	15	0.072
10	65	15	0.084
15	95	15	0.099
20	125	15	0.105
25	155	15	0.11
30	185	15	0.118

All the above-explained experiments were carried out through this study and all the results will be discovered in next chapter, and will all be discussed and analyzed in chapter 6.

CHAPTER 5

Impeller Performance Results

5.1 Introduction

As reported in chapters 2 and 3, the main purpose of this study was to investigate the effect of impeller type on concentration distribution of composite wood pellets (Brites wood pellets) in stirred reactors.

The experiments of this study were carried out with three different types of impellers; Rushton turbine impeller, pitched blade impeller and helical ribbon impeller. They are divided into two groups. First, the experiments without airflow and then, the experiments with air flow of 10 $L.min^{-1}$ and 20 $L.min^{-1}$. In all experiments, three solid concentrations were: 5wt%-10wt% and 15wt%.

In case of Rushton turbine impeller and pitched blade impeller, all experiments (with and without air flow) were carried out using five different impeller speeds of 200-400-600-800 and 1000 min^{-1} for five minutes of mixing. But in the application of helical ribbon impeller, the impeller speeds were changed from 35min^{-1} to 65-95-125-155 and 185 min^{-1} and these experiments were carried out without airflow.

In this chapter, all the experimental results are analyzed and discussed.

5.2 Morphology of the material

As mentioned before, the Brits pellets with 6mm diameter (table 1) tend to disintegrate into smaller wood particles during very short time once they are immersed in water. However, it was not clear whether the size of small particles depends on mass concentration of Brites pellets in water. It is well known that as concentration of particles in suspension increase the probability that those particles start aggregate also increases. To check whether small wood particles aggregate, the particles distributions at the range of wood concentration were measured. There suspension containing 5%, 10% and 15% by weight pellets in water were prepared and were left overnight to ensure full disintegrations of Brits pellets. The uniformity of suspensions was assed visually. Small sample of suspension was charged in cell of MasternSizer 2000 and refractive index of wood was set to 1.53 and water as dispersant had RI of 1.33. The concentration was adjusted until required beam obscuration occurred and after that the measurements were taken and particle size distributions are shown in Fig 23. The MasternSizer worked in fully automatic mode and the model necessary to fit the scattering pattern to particle size was selected automatically. General model is used for analysis.

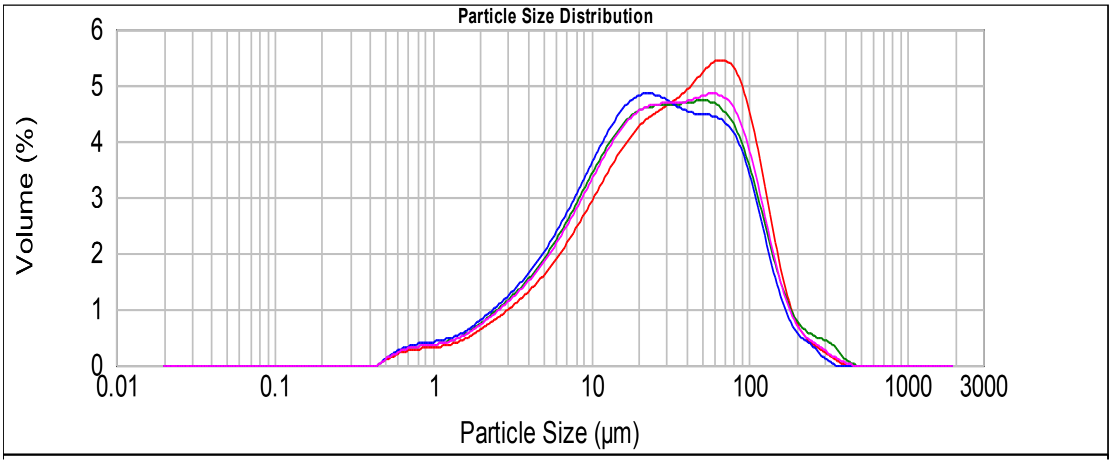


Figure 22 Particle size distributions of particles after pellets disintegrated in water from different tests. (Red line is 5 wt%, blue is 10 wt% and green is 15 wt% solid concentration).

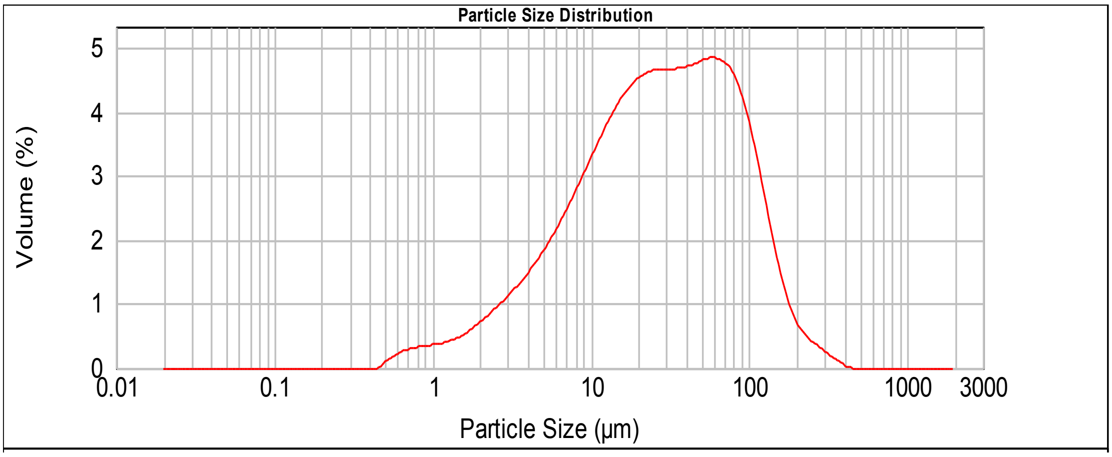
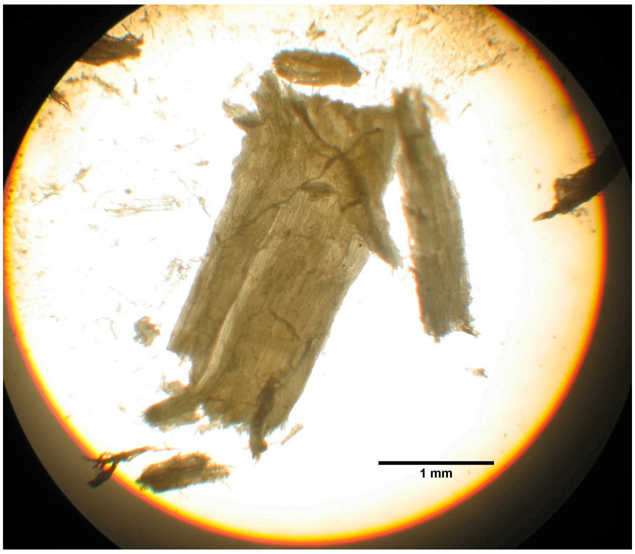


Figure 23Average particle size distribution of particles after pellets disintegrated in water.

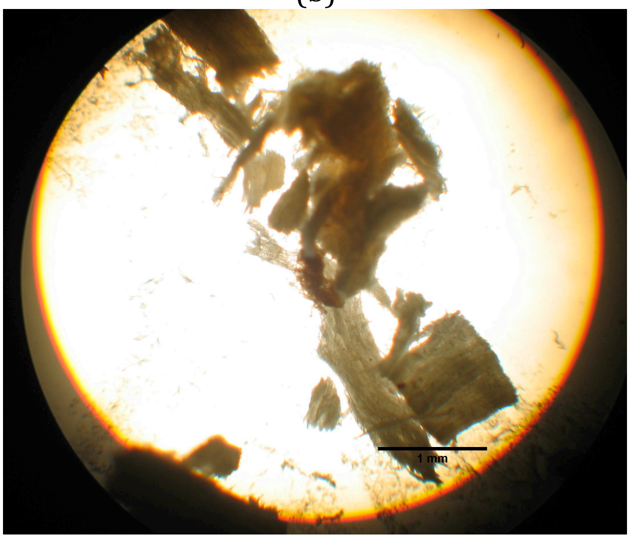
The distributions above clearly indicate that particle size is independent of concentration of wood and for all investigated concentrates the particles are in the range between XXX and YYY, and they are practically overlapping. As this was the man reason for those measurements, further analysis of size distributions involving calculations of differently defined mean diameters and other parameters quantifying distributions was not carried out.

The analysis of morphology carried out with the help of optical microscope (see below) confirmed this conclusion. Following figures show particles from samples of 5-10 and 15 wt% wood concentration.



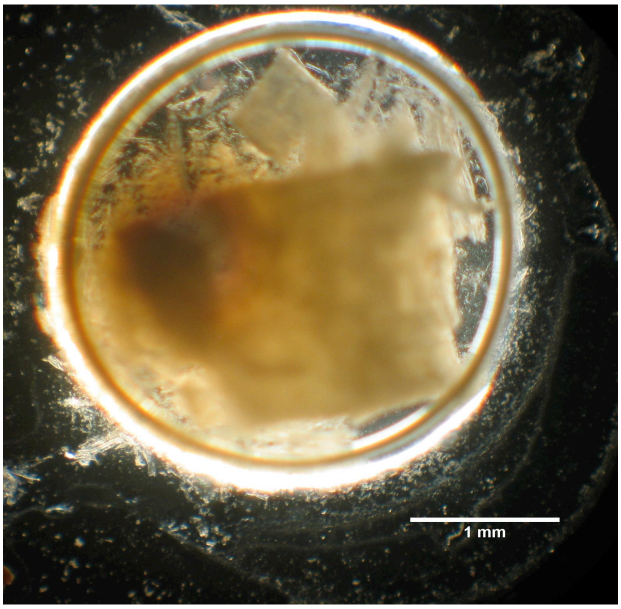
(a)

(b)

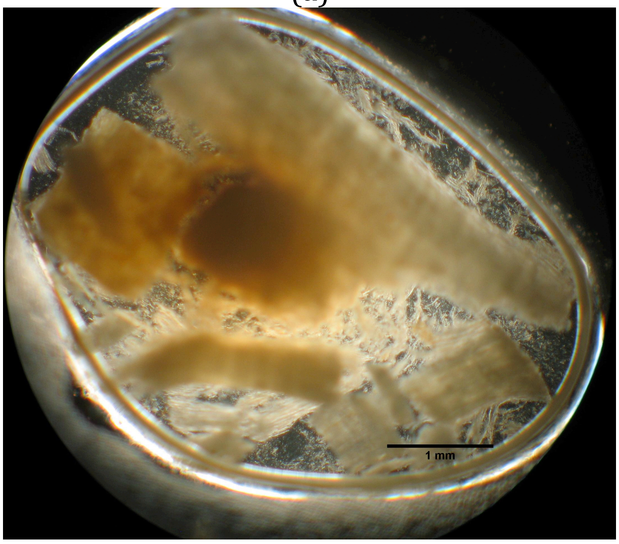


(c)

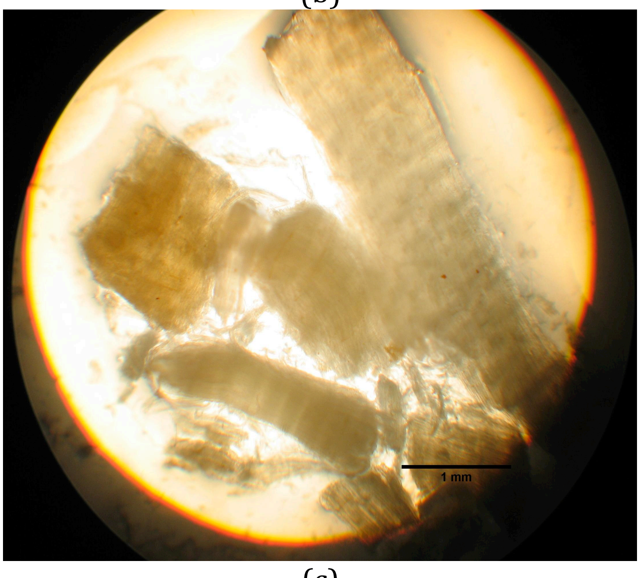
Figure 24 Dry wood particles under microscope (a) sample with 5 wt% solid (b) sample with 10wt% solid (c) sample with 15 wt% solid



(a)



(b)

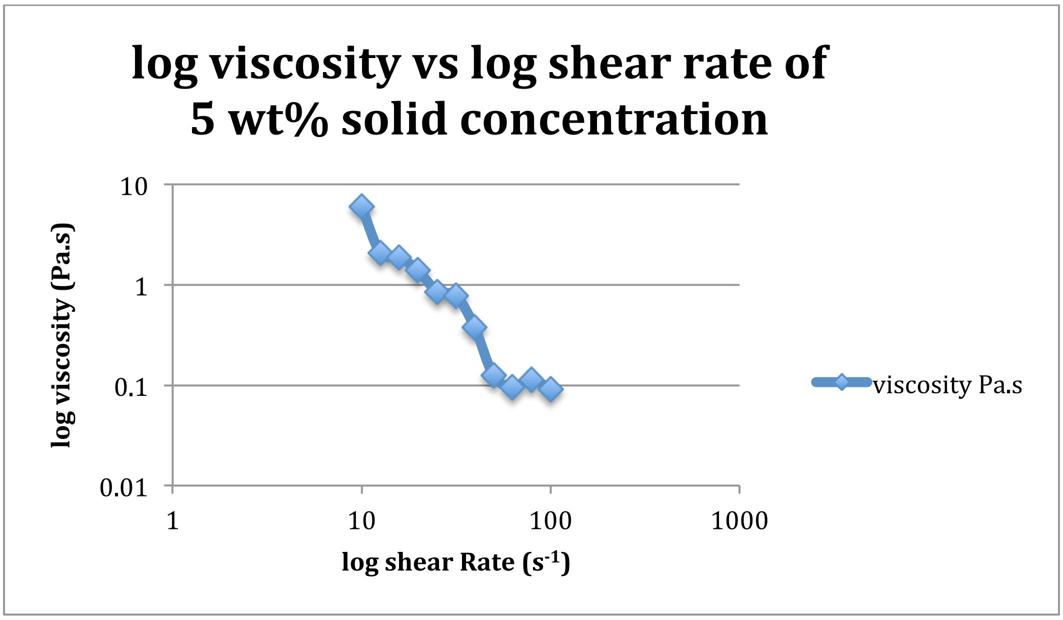


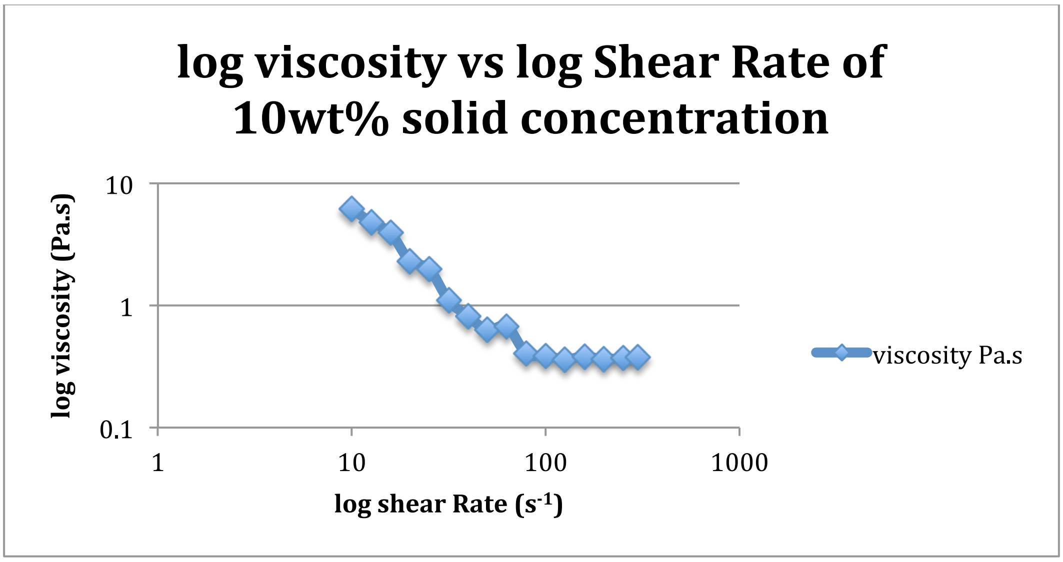
(c)

Figure 25 wet wood particles under microscope (a) sample with 5 wt% solid (b) sample with 10wt% solid (c) sample with 15 wt% solid

5.3 Rheology of the material

The following diagrams represent viscosity of the suspension of wood particles in water for each wood concentrations of 5-10 and 15 wt%, showing that suspension was a non-Newtonian and shear thinning.





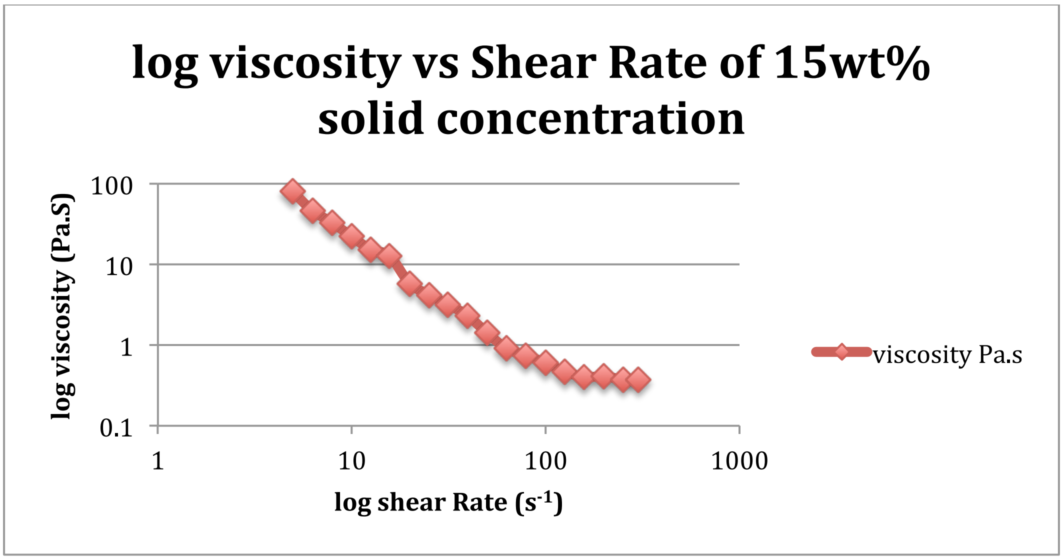


Figure 26 Log viscosities versus log shear rate diagram that shows shear thinning behaviour.

As can be seen in above diagrams, viscosity depends on concentration. It increases as solid concentration is increased.

Metzner and Otto (1957) established the best-known definition of shear rate in an agitated vessel (Grenville and Nienow, 2004). Following equation was used to calculate shear rate:

$\gamma = K_s N$ **Equation 1**

Metzner and Otto constant (Ks) for Rushton turbine and Pitched blade impeller are 11.5 and 13, respectively. And its value for Helical ribbon is 30 (Sharratt, 1996). Therefore, calculated shear rates and apparent viscosities would be as follow:

Table 11 Shear rate and apparent viscosities (using Rushton turbine impeller).

Impeller Speed (min^{-1})	Shear rate (s^{-1})	Viscosity of 5wt% concentration (Ps.a)	Viscosity of 10wt% concentration (Pa.s)	Viscosity of 15wt% concentration (Pa.s)
200	38	1.39	0.81	2.32
400	76	0.37	0.4	0.74
600	115	0.1	0.38	0.5
800	153	0.1	0.38	0.4
1000	191	0.09	0.36	0.4

Table 12 Shear rate and apparent viscosities (using Pitched blade impeller).

Impeller Speed (min^{-1})	Shear rate (s^{-1})	Viscosity of 5wt% concentration (Ps.a)	Viscosity of 10wt% concentration (Pa.s)	Viscosity of 15wt% concentration (Pa.s)
200	43	1.3	0.81	2.3
400	86	0.2	0.4	0.7
600	130	0.09	0.36	0.46
800	173	0.09	0.35	0.4
1000	215	0.02	0.33	0.3

Table 13 Shear rate and apparent viscosities (using helical ribbon impeller).

Impeller Speed (min^{-1})	Shear rate (s^{-1})	Viscosity of 5wt% concentration (Ps.a)	Viscosity of 10wt% concentration (Pa.s)	Viscosity of 15wt% concentration (Pa.s)
35	18	4	3.5	12.6
65	32	1.8	1.0	3.1
95	48	0.8	0.7	1.4
125	62	0.7	0.6	0.9
155	78	0.3	0.4	0.7
185	92	0.2	0.4	0.65

The behavior of a shear-thinning fluid can be defined mathematically by the *power law,* which relates the shear stress in the fluid to the shear rate being applied on it (Grenville and Nienow, 2004):

$$\boldsymbol{\tau = K\gamma^{n}} \quad \textbf{Equation 2}$$

Therefore, dynamic viscosity would be (Grenville and Nienow, 2004):

$$\boldsymbol{\mu_A = \frac{\tau}{\gamma} = K\gamma^{n-1}} \quad \textbf{Equation 3}$$

Where μ_A is the apparent viscosity of the fluid, and K and n are the consistency and flow behavior index, respectively (Grenville and Nienow, 2004). As apparent viscosity and shear rate are calculated, n can be estimated by equation-3. Studying n proved a shear-thinning fluid while n was less than one.

For the purpose of this work the power law model is sufficient to compare between different wood concentrations therefore more advanced models were not considered.

5.4 Impeller Performance

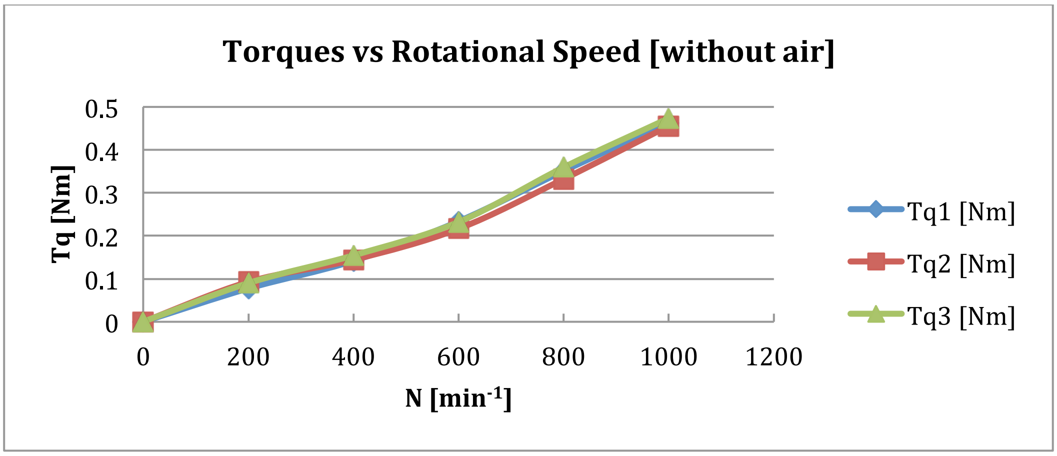
Generally, in industrial applications, the power consumption per unit volume of fluid is used for a scale-up, scale-down and design. In spite of extensive use, only the effect of power consumption on the impeller type/speed and tank geometry is well understood. This is partially because of the difficulties in accurate measurements of torque on the small scale (Chapple, Kresta et al., 2002). This complexity was apparent in this study, so the average torques were used to calculate the power consumption and energy dissipation rates.

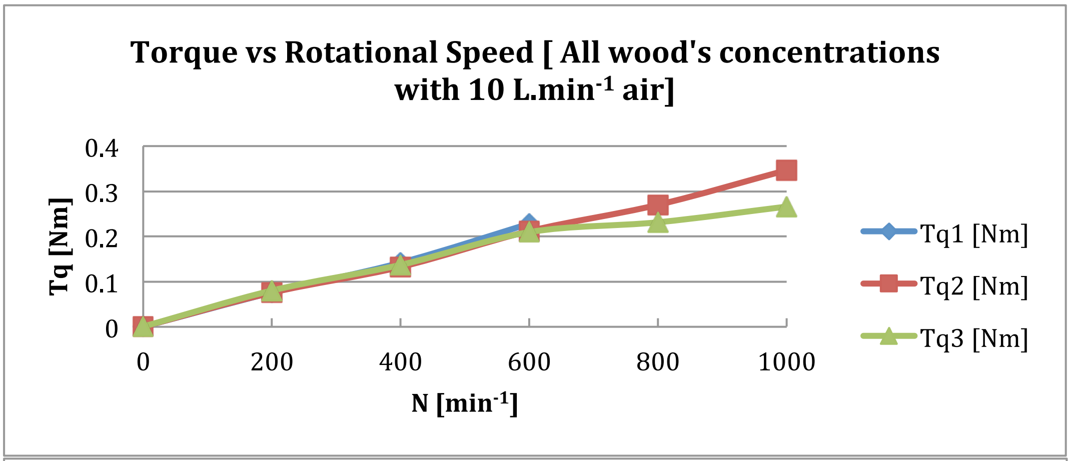
5.4.1 Torque measurements

Generally, torque is the product of tangential force and arm this force is acting on resulting in body rotation. It is represented as a moment vector of a force and its measurement is usually needed in several engineering fields, particularly in rotating machines (Rangan, Sarma et al., 1997) such as a stirred vessel.

5.4.1.1 Torque measurements of Rushton turbine impeller

In following diagrams, torque is measured for each speed of Rushton turbine impeller. In all graphs, T_1, T_2 and T_3 represent measured torques of 5, 10 and 15 wt% concentration of wood pellets, respectively.





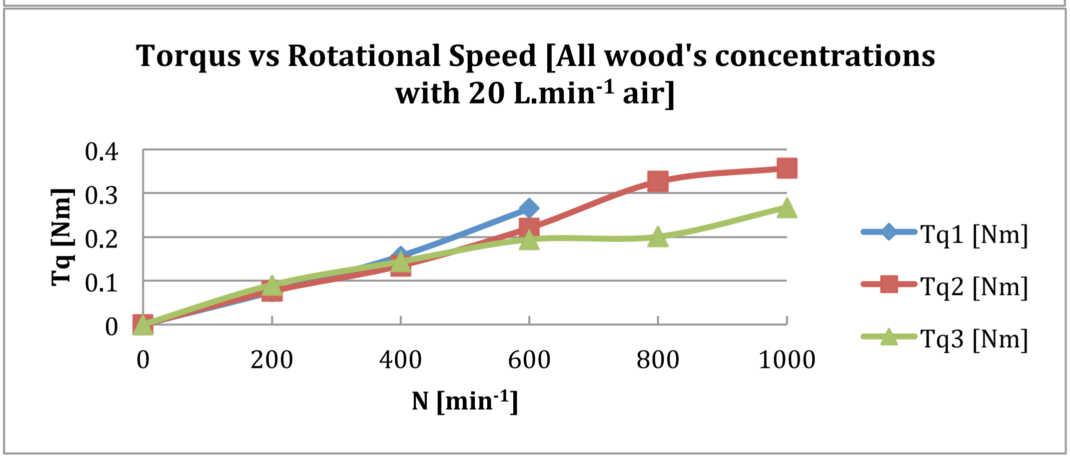


Figure 27 Torque versus rotational speed of all solid concentrations using Rushton turbine impeller.

In this study most values of torques (in presence and in absence of air) are summarized. The values, which are not mentioned, are the ones, which could not be measure because in those conditions water has overflowed, and fallen out of the vessel.

As can be seen in above diagrams, torques of all solid concentrations of 5-10 and 15wt% with no airflow rates are approximately equal. At air flow rate of 10

$L.min^{-1}$ the torques of all concentrations of 5-10 and 15wt% are approximately equal but for impellers speed higher than 600 min^{-1}, solid concentration of 15wt% has less torques compared to two other solid concentration. And finally, at flow rate of 20 $L.min^{-1}$, the three concentrations has approximately equal torques but for impeller speeds of higher than 400rpm, 10 wt% solid has less toque compared to 5 wt% and 15wt% solid has less torques than 10 wt%.

Here it can be concluded that when the air is sparged in the vessel, torque depends on concentration at some impeller speeds.

5.4.1.2 Torque measurements of Pitched Blade Impeller

In the following diagrams and tables, torque is measured using Pitched blade impeller. In all graphs, T_1, T_2 and T_3 represent measured torques of 5, 10 and 15 wt% wood pellets, respectively.

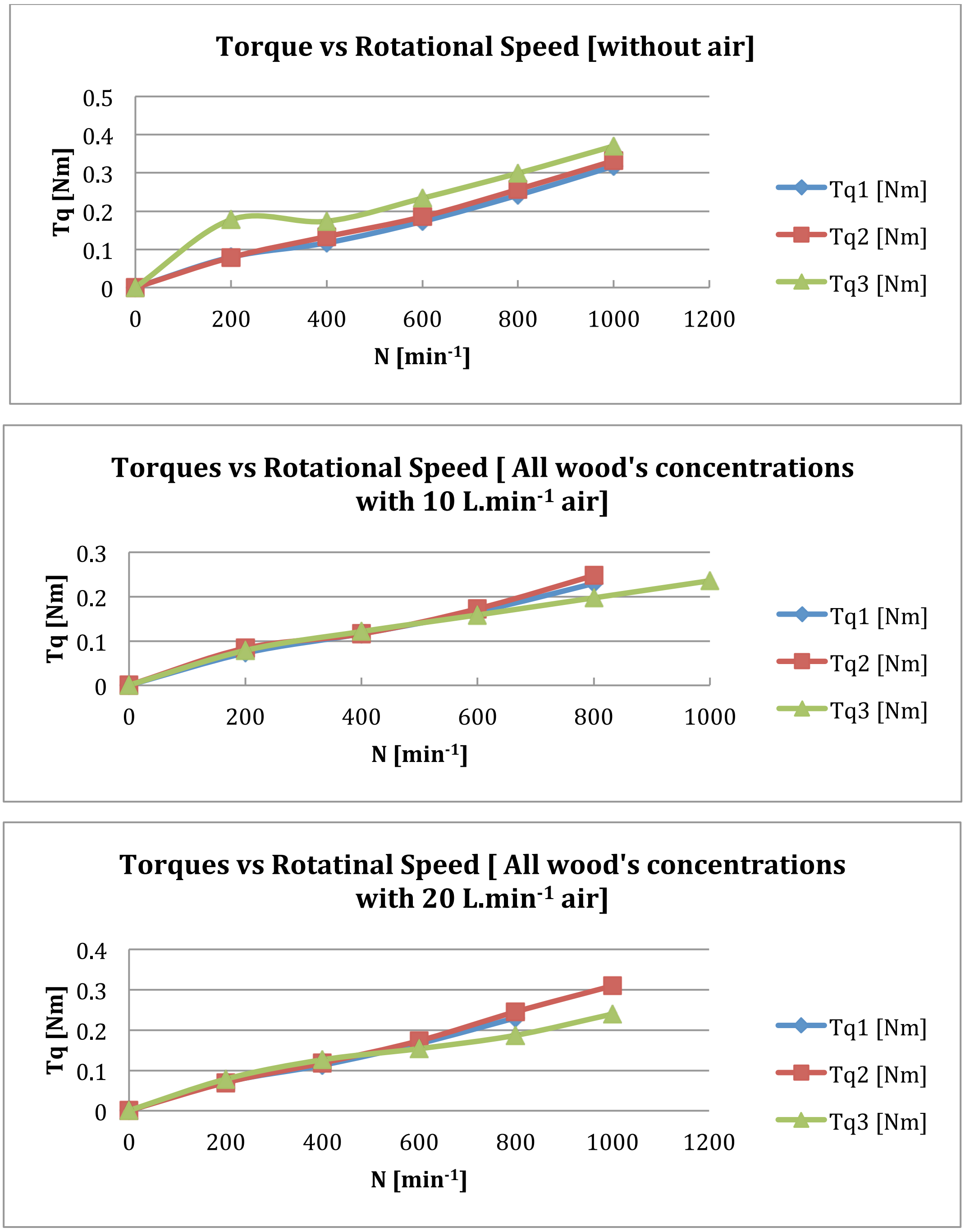


Figure 28 Torque vs. rotational speed of all solid concentrations using pitched blade impeller.

As can be seen in above figures, it is found out that at air flow rate of zero, toques of 5 and 10 wt% solids are approximately equal but they are less than 15 wt% solid. At airflow rate of 10 and 20 L.min^{-1}, all three concentrations has equal torques but at impeller speeds of higher than 600 min^{-1}, 15 wt% solid has less torque than two others.

Comparing toques of Rushton Turbine with Pitched blade shows that for each solid concentration, Pitched blade impeller has lower torques at the same speed than the Rushton Turbine, as D and P_0 of this Pitched blade impeller are smaller.

5.4.1.3 Torque measurements of helical ribbon screw impeller

The following diagrams show torques measured for helical ribbon impeller. In all graphs, T_1, T_2 and T_3 represent measured torques of 5, 10 and 15wt% wood, respectively. In this case, the experiments were carried out without air due to the reasons, which have been explained in chapter 4.

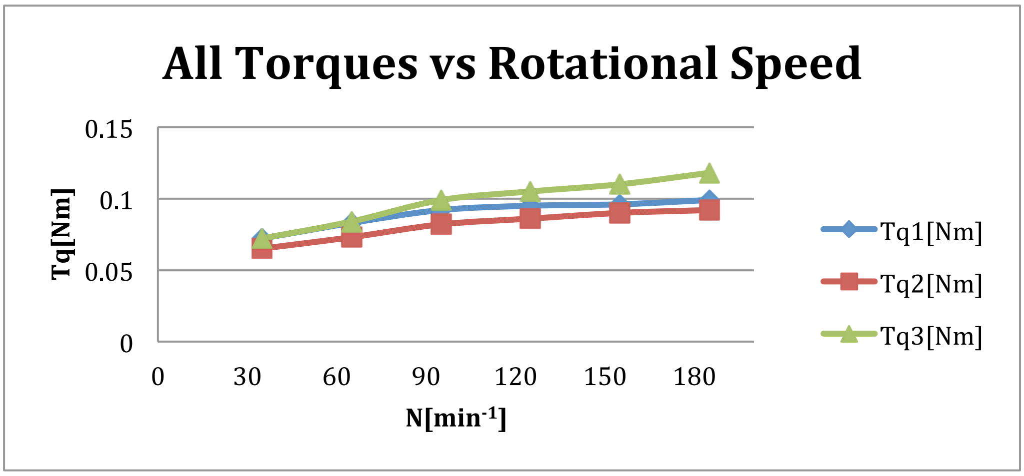


Figure 29 Torque versus rotational speed of all solid concentration using helical ribbon screw impeller.

5.4.2 Power draw calculations

5.4.2.1 Power draw estimation (Rushton turbine and pitched blade impeller)

The power delivered to the fluid is the product of the impeller speed and torque on the impeller blade (Grenville and Nienow, 2004):

$P = 2\pi NTq$ **Equation 4**

Tables (5-i) and (5-ii) in appendix show the power requirements of Rushton turbine and Pitched blade impeller in presence and absence of air.

5.4.2.2 Power draw calculation (helical ribbon screw impeller)

As reported previously, experimental power requirement can be estimated by Equation (4). Table (5-iii) shows the power consumption when using helical ribbon screw with no airflow.

Results show that power consumption of pitched blade impeller is less than power consumption of Rushton Turbine impeller. But it seems that the power demand of helical ribbon screw impeller is higher than the other two impellers.

5.4.3 Power Number calculations

Estimation of the power draw and energy dissipation rate is straightforward if torque and impeller speed are measured accurately. In a stirred-tank mixings, the most basic measurement is the power draw of the system, as many scale-up rules based on power draw or energy dissipation rates. The power draw, P, can be calculated from (Grenville and Nienow, 2004):

$$P=P_0.\rho N^3D^5 \qquad \textbf{Equation 5}$$

In general, the value of power number is affected by geometric factors such as number of impeller blades, impeller tip chord angle, the number and dimensions of baffles and also the position of the impeller within the vessel (Ende, 2011).

As experimental power consumptions are calculated by Equation (4) power Numbers can be estimated by Equation (5) which are stated in appendix as table (5-iv), (5-v) and (5-vi). Here, power Numbers come from torque.

For turbulent flows, constant values of P_o can differ by an order of magnitude depending on impeller design. The blade width and the number of blades strongly influence P_o. Mostly, the effect of blade width can be stated as $P_o \propto (w/D)^{0.65}$ for four-bladed 45^o pitched impeller and $P_o \propto (w/D)^{1.45}$ for six-bladed Rushton turbines. And within the ranges of what used in stirred tank, P_o is uncertainly affected by C/T and D/T (0.33-0.5). And also, stirred vessels should not be operated at Re <1000 for most duties using these what impellers because of the lack of turbulence decreases the level of mixing performance to an improper level (Stitt and Simmons, 2011).

5.4.4 Reynolds Number calculation

Following equation (Grenville and Nienow, 2004) was used in order to calculate Reynolds Numbers. Reynolds Numbers are calculated according to the viscosities of table 11, 12 and 13.

$Re = ND^2\rho/ \mu$ Equation 6

Table 14 calculated Reynolds Numbers, using Rushton Turbine impeller.

Impeller Speed (min^{-1})	Reynolds Number of 5wt% solid	Reynolds Number of 10wt% solid	Reynolds Number of 15wt% solid
200	13	23	8
400	102	96	53
600	571	153	119
800	760	204	198
1000	1053	269	246

Table 15 Calculated Reynolds Numbers, using Pitched blade impeller.

Impeller Speed (min^{-1})	Reynolds Number of 5wt% solid	Reynolds Number of 10wt% solid	Reynolds Number of 15wt% solid
200	13	20	7
400	165	84	49
600	555	141	113
800	738	193	173
1000	4148	256	287

Table 16 Calculated Reynolds Numbers, using Helical screw impeller.

Impeller Speed (min^{-1})	Reynolds Number of 5wt% solid	Reynolds Number of 10wt% solid	Reynolds Number of 15wt% solid
35	0.62	0.7	0.2
65	2.5	5	1.5
95	8	10	5
125	12	15	10
155	37	28	16
185	66	33	21

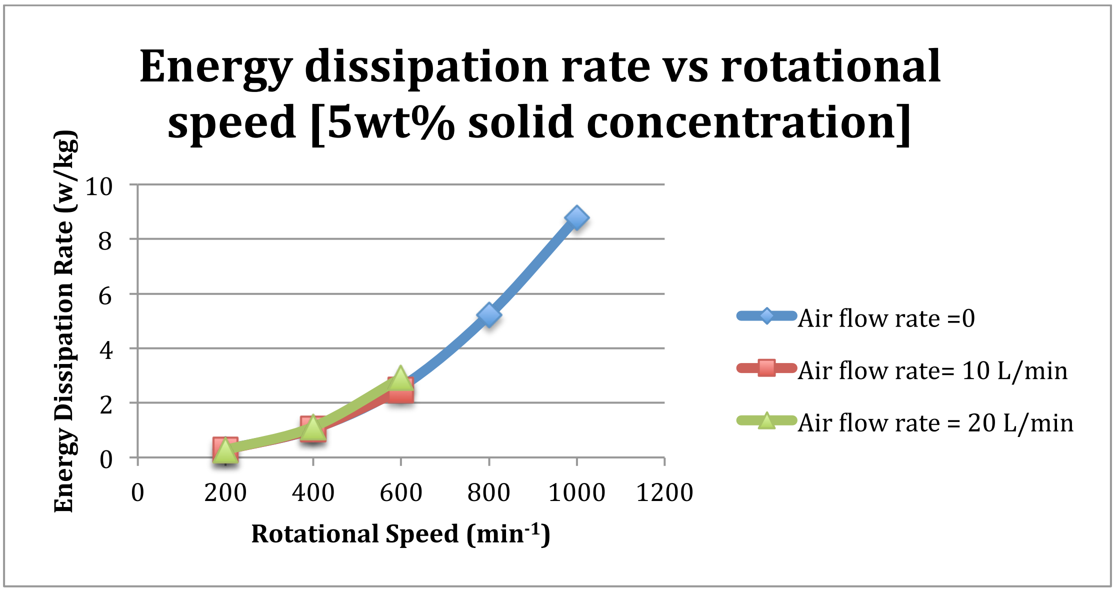
5.4.5 Energy dissipation rate

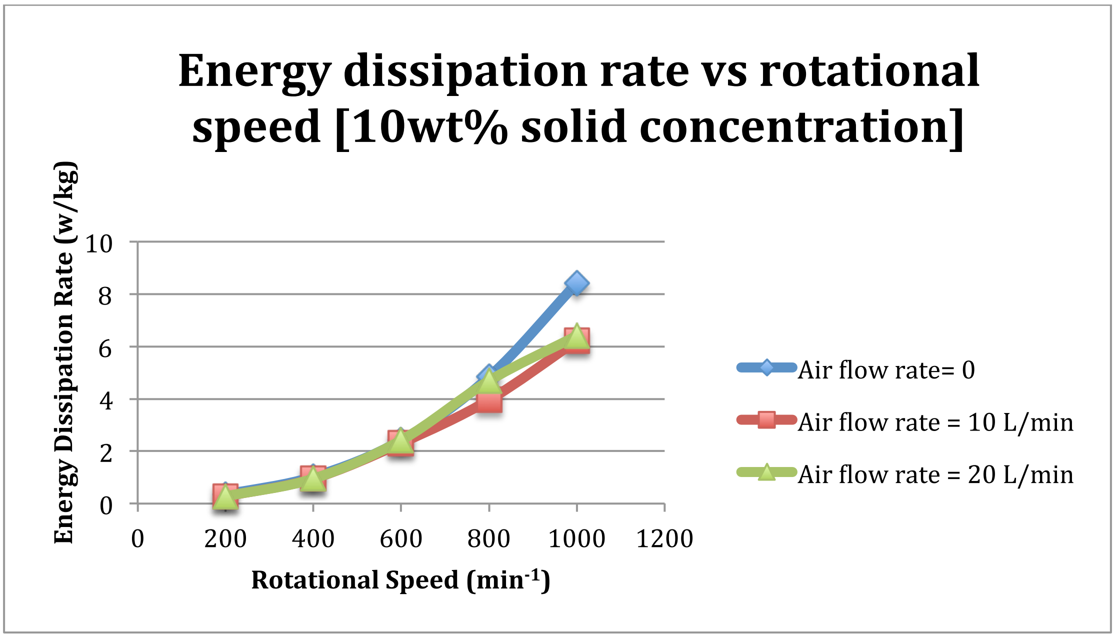
In majority of application calculating energy dissipation rates rather than power input is used (Ein-Mozaffari, Kammer et al. 2004) in which ε_{avg} is equivalent to the specific power dissipation throughout the vessel:

$$\varepsilon_{avg} = P/\rho V \qquad \textbf{Equation 7}$$

5.4.5.1 Energy dissipation rate of using Rushton turbine impeller

The following graphs illustrate all energy dissipation rates of all three concentrations with and without air.





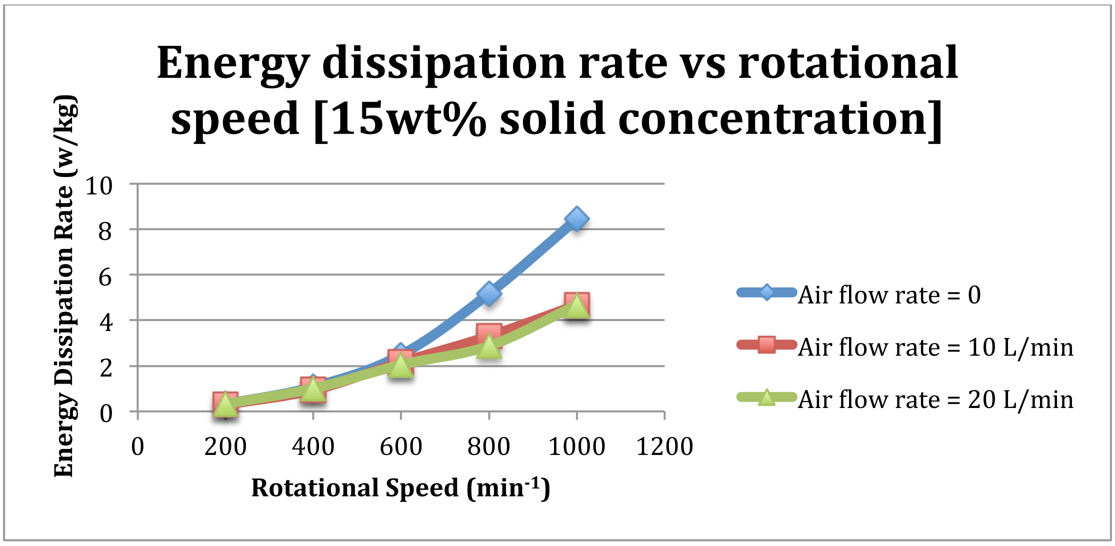


Figure 30 Energy dissipation rate of using Rushton turbine impeller.

As can be seen in above diagrams, at 5wt% solid concentration, energy dissipation rate is independent of airflow. At 10 wt% solid, it is independent as well but at impeller speeds of higher than 600 rpm it decreases at 10 $L.min^{-1}$ air flow but again increases at 20 $L.min^{-1}$. Finally, at 15 wt% solid concentration, energy dissipation rates are independent of air flow but this fact changes at impeller speeds of higher than 600 min^{-1}. In this condition when air is sparged, energy dissipation rates have decreased but did not change by increasing airflow rate from 10 to 20 $L.min^{-1}$.

5.4.5.2 Energy dissipation rate of using pitched blade impeller

The following graphs illustrate energy dissipation rates of all three wood pellets' concentrations with and without air.

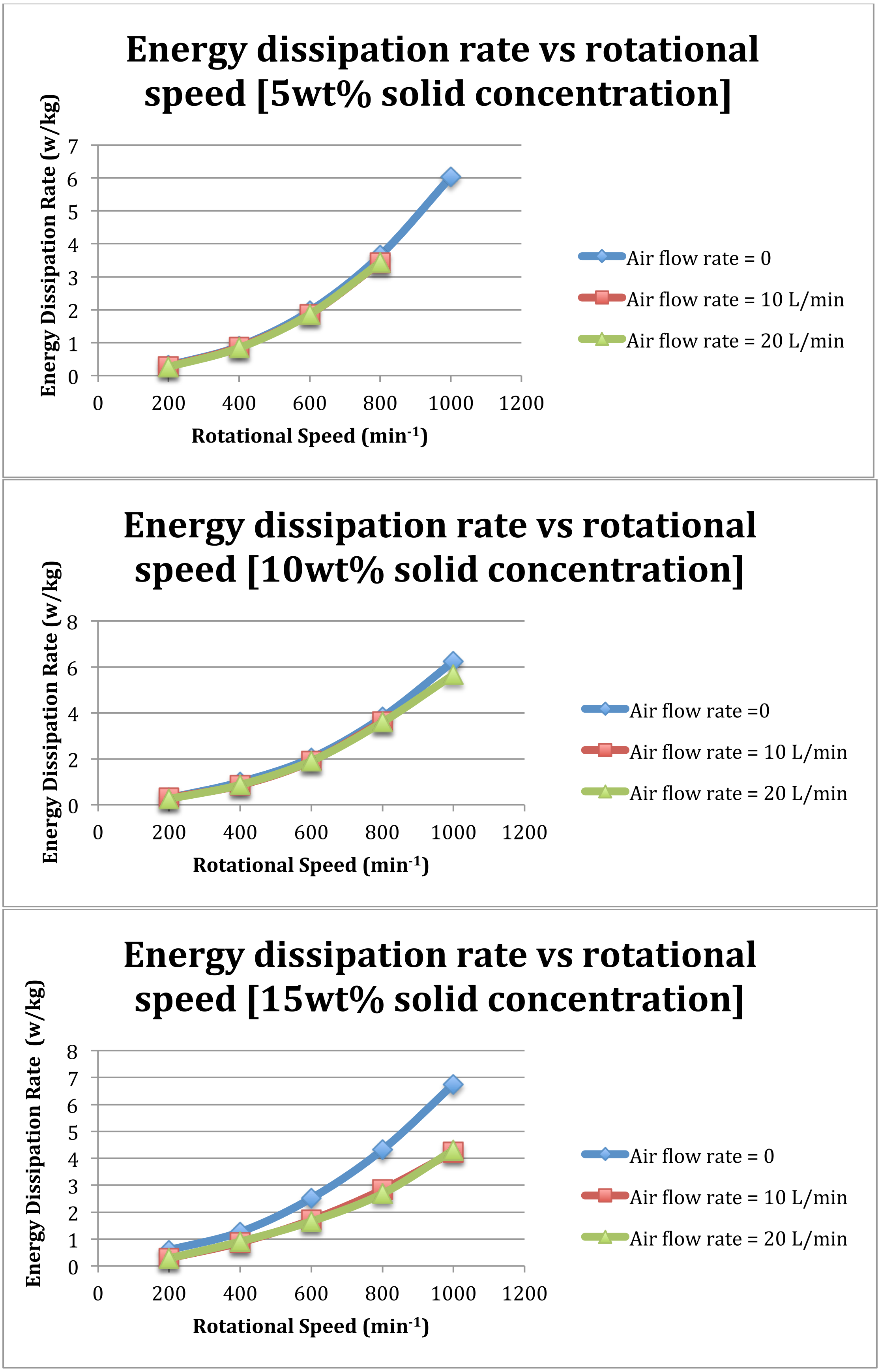


Figure 31 Energy dissipation rates of using pitched blade impeller.

As can be seen in above diagrams, using Pitched blade impeller shows that for 5 wt% and 10 wt% solid concentration, energy dissipation rate is totally independent of air flow. This means that increasing airflow did not change energy dissipation rate. But at 15 wt% solid concentration, sparging air through the vessel has decreased the energy dissipation rate.

5.4.5.3 Energy dissipation rate of using helical ribbon screw impeller

The following graphs show torque and energy dissipation rates at all three wood pellets concentrations.

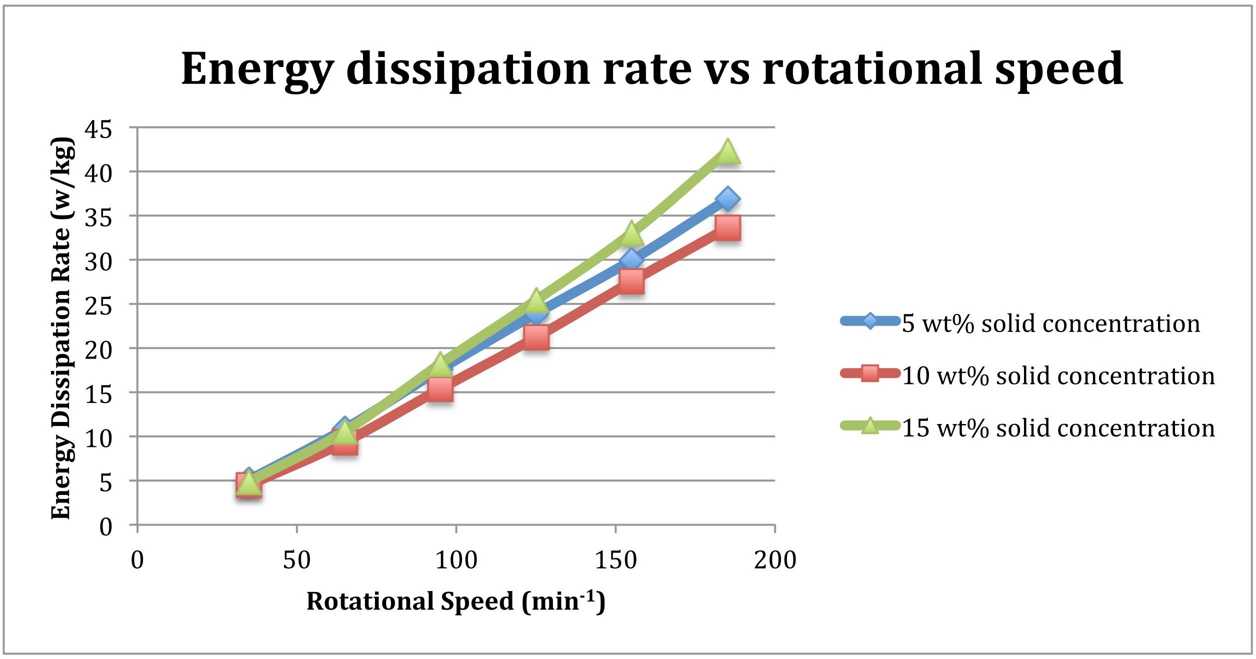


Figure 32 Energy dissipation rates of helical ribbon impeller.

Above diagram shows that increasing solid concentration slightly change energy dissipation rate in the experiments using Helical Ribbon impeller.

5.5 Minimum impeller speed (N_{JS}) measurements

In chapter 3, the minimum impeller speed and three different techniques of measuring were discussed. To produce complete off-bottom suspension, the minimum impeller speed is required. A number of researchers have measured N_{js} using different devices and methods, but the most common is still Zwietering's correlation (Cullen, 2009).

$N_{js} = S\, \nu^{0.1}\, d_p^{\ 0.2}\, [\frac{g\Delta\rho}{\rho L}]^{\ 0.45}\, D^{-0.85}\, X^{0.13}$ (7)

This dimensionless parameter related to geometrical affects including off-bottom clearance, impeller to tank diameter ratio and impeller type (Cullen, 2009). With S= 4.8 for Rushton Turbine and S= 3.69 for Pitched Blade impeller, following table shows N_{js} for Rushton Turbine and Pitched blade impeller (Jafari, Tanguy et al., 2012). These minimum impeller speeds compared to the minimum impeller speeds, which were observed, are very small and that might be because of the rheological complexity of this study.

Table 17 calculated minimum impeller speeds

Impeller	Minimum impeller speed (min^{-1})
Rushton turbine (5wt% solid concentration)	178
Rushton turbine (10wt% solid concentration)	195
Rushton turbine (15wt% solid concentration)	208
Pitched blade (5wt% solid concentration)	141
Pitched blade (10wt% solid concentration)	154
Pitched blade (15wt% solid concentration)	165

The visual observation technique described previously, was used to determine N_{js} in experiments using: Rushton Turbine, Pitched Blade and Helical s impeller) and the results are summarized in the following tables. Since, the stirred vessel bottom were not transparent, the vessel was illuminated and viewed from the side. Zwietering criterion defines N_{js} as the minimum speed at which particles do not remain at rest on the bottom of the vessel for more than one or two seconds before being picked up, so the suspension can be considered as "just complete" (Ghionzoli, Bujalski et al., 2007).

In all tables (tables (5-vii), (5-viii) and (5-ix)), it should be noted that at solid concentration equal to 15 wt %, there was no motion even in presence of air. So under these conditions, minimum impeller speed (N_{js}) did not exist (within investigated range).

As the tables show, there is a huge difference between the results of minimum impeller speed of this study with the reported studies of other researchers. In this research, by increasing the airflow rate the minimum impeller speed decreased while other researchers reported that by increasing airflow rate, the minimum impeller speed would increase. These results are discussed in chapter 6 (Results Discussions). Torque and minimum impeller speed for each impeller were measured and power consumptions and energy dissipation rates were estimated. This chapter summarized all the results of each experiment, where carried out in this study. The results and the potential reason for discrepancy are discussed in detail in chapter 6.

CHAPTER 6

Discussion and Conclusions

6.1 Discussion and conclusions

As mentioned in previous chapters, the main purpose of this research is to evaluate the effect of impeller type on the hydrodynamics and concentration distribution of composite wood pellets suspended in water in a stirred vessel. Investigating the behavior of wood pellets was related to the fact that nowadays, in industry, it is preferred to use biomass to manufacture fine chemicals instead of fossil fuels and oil. The chemicals and pharmaceutical products such as acetic acid, furfural, itaconic acid, lactic acid, succinic acid, vanillin as well as hydrogen and methanol can be produced from woody biomasses (MacKay, Cole et al., 2009). This research is a first part of such research and it is focused on hydrodynamics and concentration distribution of wood pellets composite (Brites wood pellets) suspended in water.

All results are summarized in chapter 4 and in this chapter the results are compared and discuss in order to recommend a suitable operation conditions and impeller type for further studies.

6.2 Operating Conditions

6.2.1 Solid Concentration

As reported in chapter 4, three different solid concentration of 5,10 and 15wt% were evaluated. It was found that the 15wt % of wood pellet as solid phase is too high and it was not possible to develop uniform suspension of solid through the vessel. During the experiments at 15wt% solid concentration it was very clear that there were no movement of wood particles even at 1000 min^{-1}. Also this condition was repeated with air entering the vessel. The airflow rate was increased from 10 $L.min^{-1}$ to 20 $L.min^{-1}$ but it was still impossible to suspend the wood in the liquid phase. At this concentration the whole wood pellets were observed up to the water level. The stationary wood pellet particles can be seen in the figure below, and this phenomenon was observed with all impeller types. Also as mentioned in chapter 3, Ein-Mozaffari et al. (Ein-Mozaffari et al., 2003) has improved In numerous cases, the suspension volume involved in active mixing was only 20 to 40% of that in the chest. The unfavorable flows responsible for this occur due to the complex rheology of the pulp suspensions.

Figure 33 Stationary pellets at the top of the vessel at 15% wood with/without air flow.

According to the results it can be concluded that the solid concentration of 15wt% is too high for this type of wood and maximum solid concentration where mixing was adequate was 10wt%.

6.2.2 Impeller Speed

One of the most important parameters, which should be considered in order to achieve complete suspension in mixing processes, is impeller speed. At a low impeller speed of 200 min^{-1} (for 5-10 wt% of solid concentration) the majority of the particles rested on the bottom of the vessel. As impeller speed was increased solid particles were pushed by the impeller and moved to the periphery of the vessel. Also, two regions on the bottom of the vessel were observed, one region was at the center circle region and other an outer annular ring region. It was clear that the diameter of the center circle was about the diameter of the impeller. As the impeller speed was increased, most wood particles were lifted from the periphery were they were gradually suspended by the upward liquid flow along the tank walls until all particles were suspended. The wood/particles were lifted from the solids layer formed on the bottom of the vessel with the recirculation flows as observed by (Dohi, Takahashi et al., 2004).

6.3 Minimum Impeller Speed (N_{js})

It is important to know the minimum impeller speed in which the mixing process can take place. In all experiments, when the impeller started to rotate, all solid particles formed a particle pile, on the tank bottom. The both N_{jsg} and N_{js} depend on impeller size, impeller type, solid concentration, tank geometry, solid size and so on (Zhu and Wu, 2002).

The results of measuring the minimum impeller speed for “just complete suspension” shows that N_{js} is a function of solid concentration. As solid concentration increases, N_{js} increases as well. This happened with all three impellers as previously observed by (Ghionzoli, Bujalski et al., 2007).

6.3.1 Effect of gas flow on N_{js} and N_{jsg}

In aeration experiments, wood particles had lifted without agitation and this shows that airflow could help solid particles to lift and suspend through the stirred vessel. This can be the main reason that N_{jsg} is less than the N_{js} in such experiments (Dohi, Takahashi et al., 2004). As described previously in chapter 4, the way that air is introduced to the stirred vessel in this study is totally different from other works, which have been done by other researchers. In other studies, air entered the stirred vessel from the bottom of the tank while in this work; it is entered from tom of the tank using a plastic pipe.

After all observations, it can be concluded that by introducing the gas flow from the top of the vessel the solid particles are suspended just as gas bubbles are first being circulated down the vessel walls towards the base. This technique can be a great help for further work to reduce power consumption and be economical due to the decrease of operational costs.

6.4 Rheology of the wood suspension

6.4.1 Particle size

As mention in chapter 2, in previous studies, length and diameter of wood pulp fibres are reported 1-3 mm and 15-30 μm, respectively (Derakhshandeh, Kerekes et al., 2011). Accordingly, size distribution of wood pellets was observed and figured out that the mean particle size was around 30μm and the lengths of the most fibres are more than 1mm.

Besides, by comparing the same figures (figure 24 and 25) it can be concluded that the fibres of wet sample are clearer than the dry one. Furthermore, the dry ones have more sharp edges than the wet one. Also it appears that the dry ones are denser than the ones, which are put in water. This is improved by estimating of the pellets' density (1400 kg.m^{-3}) and the suspension densities of (1020, 1040 and 1060 kg.m^{-3}).

6.4.2 Flow behavior

In the experiments of this study the shear thinning behavior of the suspension was observed as well and also according to the following figure, it can be concluded that by increasing wood concentration, viscosity of the suspension increases, too, as Blakeney (Blakeney, 1966) and Chase et al. (Chase, Donatelli et al., 1989) has faced this fact in their studies (Derakhshandeh et al. 2011).

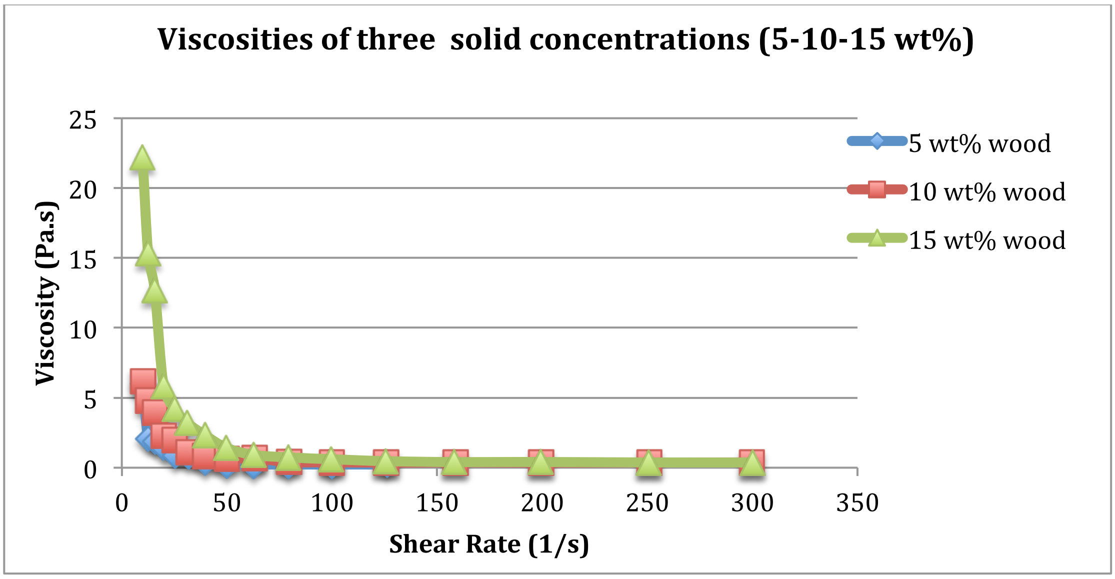


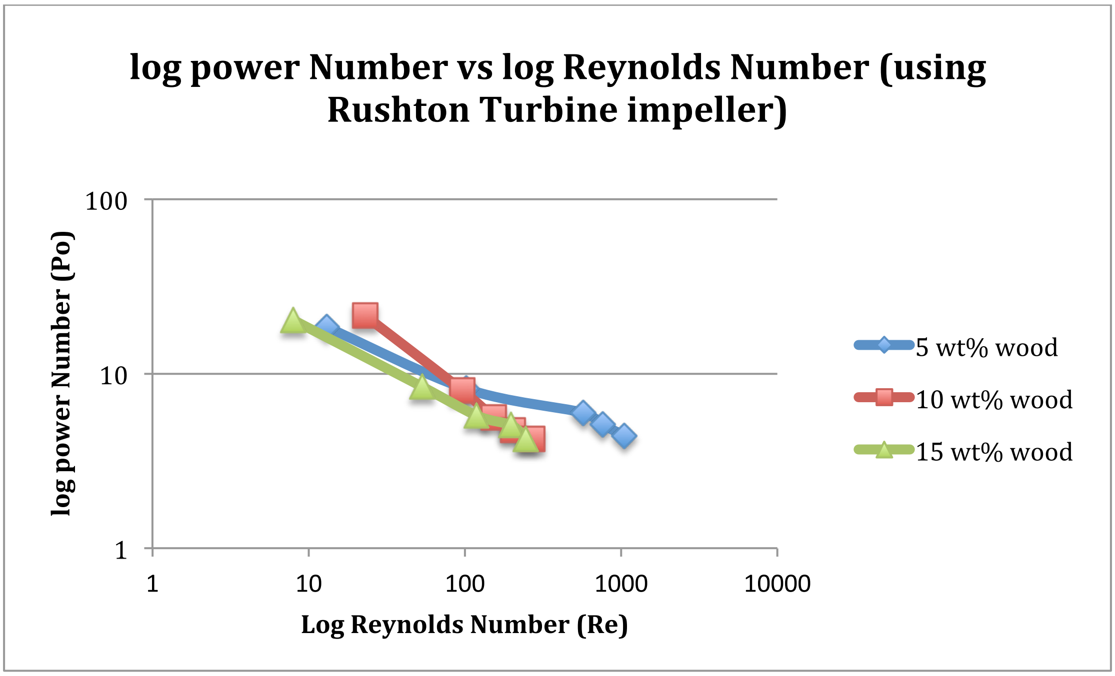
Figure 34 Comparison of viscosities of three solid concentrations.

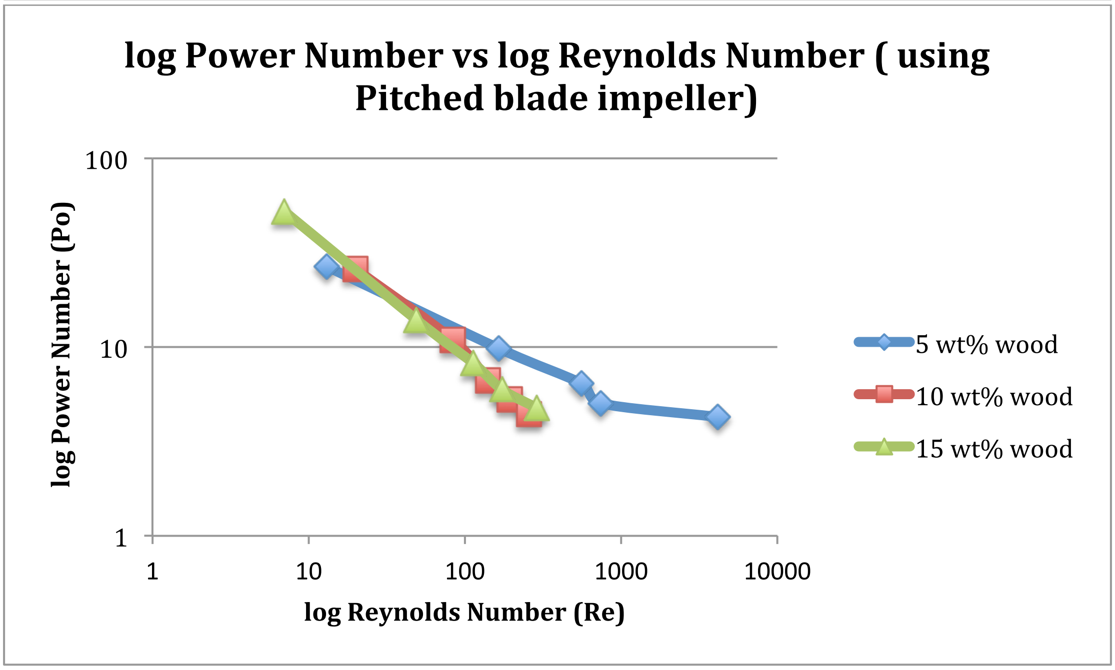
To the engineering approximation at shear rates higher then 100 (s^{-1}) the suspension can be treated as Newtonian.

6.5 Impeller Characterization

Mostly, impellers are characterized by their power number, P_0, and Reynolds Numbers, Re. P_0 is correlated with Re as shown in following figures. Figures illustrates that the curves collapse to a single operational curve for either 10 or 15 wt% wood concentrations using Rushton Turbine and Pitched blade and for all wood concentrations (5-10-15 wt%) using helical screw impeller.

Also from these figure we can conclude that there is turbulent flow, using Rushton Turbine impeller and Pitched blade impeller and laminar flow using Helical screw impeller.





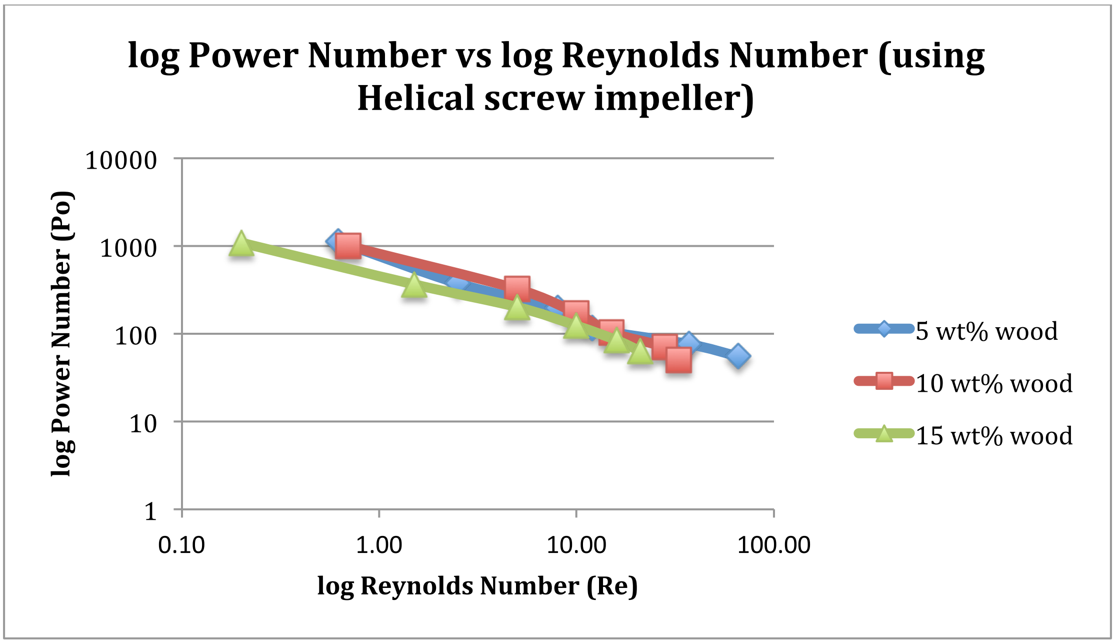
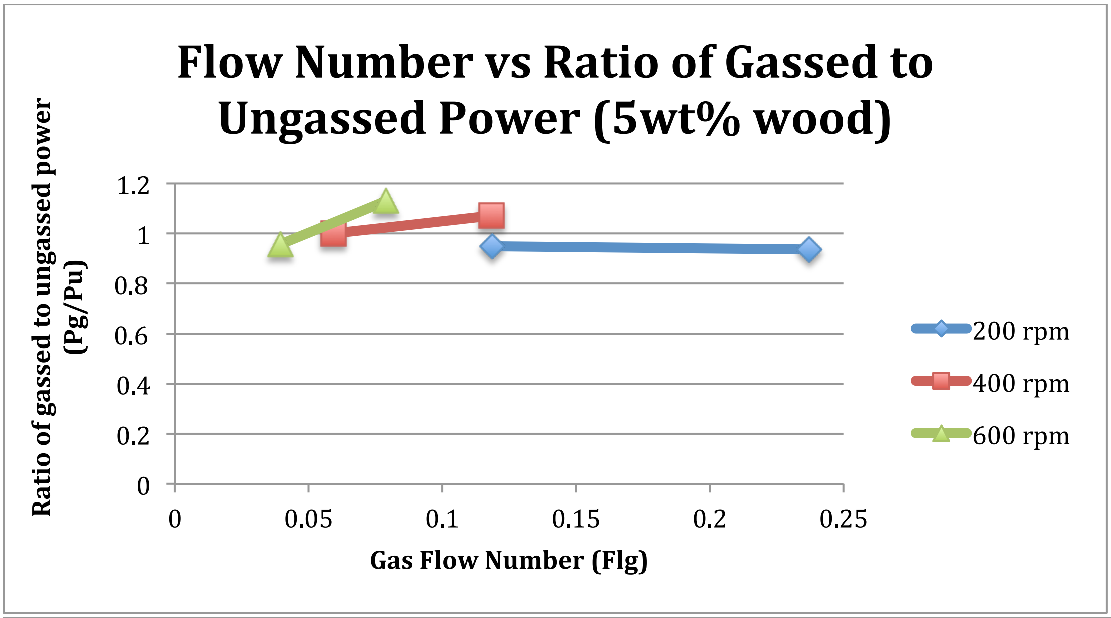


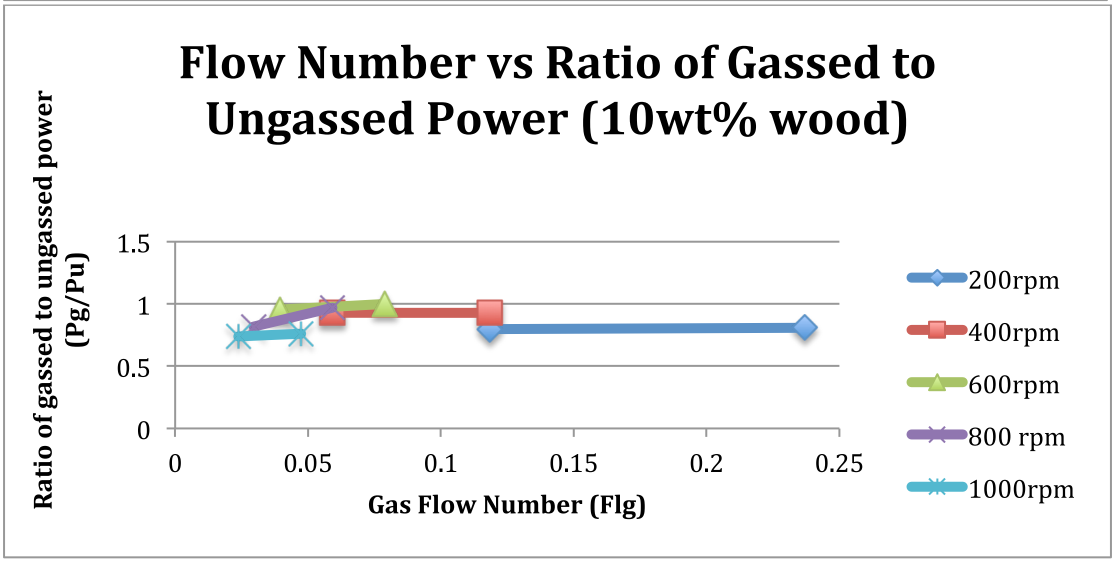
Figure 35 log Power Number versus log Reynolds Numbers

6.6 Gassed Suspension

6.6.1 Experiments of using Rushton Turbine impeller

When gas is sparged into liquid, it reduces the power requirements for stirring (Doran, 2013). Besides in chapter 5 all calculated power drawns are gathered which improve this fact. But it was necessary to compare the difference of power consumptions of sparging 10 $L.min^{-1}$ and 20 $L.min^{-1}$ air with each other. Following figures shows that in this study increasing gas flow rate necessarily did not decrease power consumption but also at some impeller speeds, increasing gas flow rate increases power consumptions.





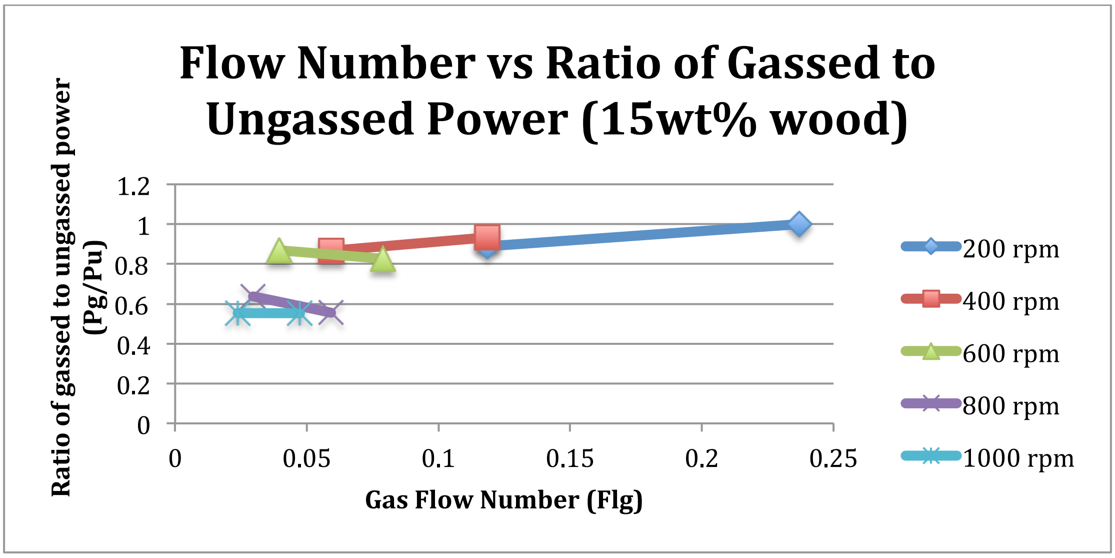
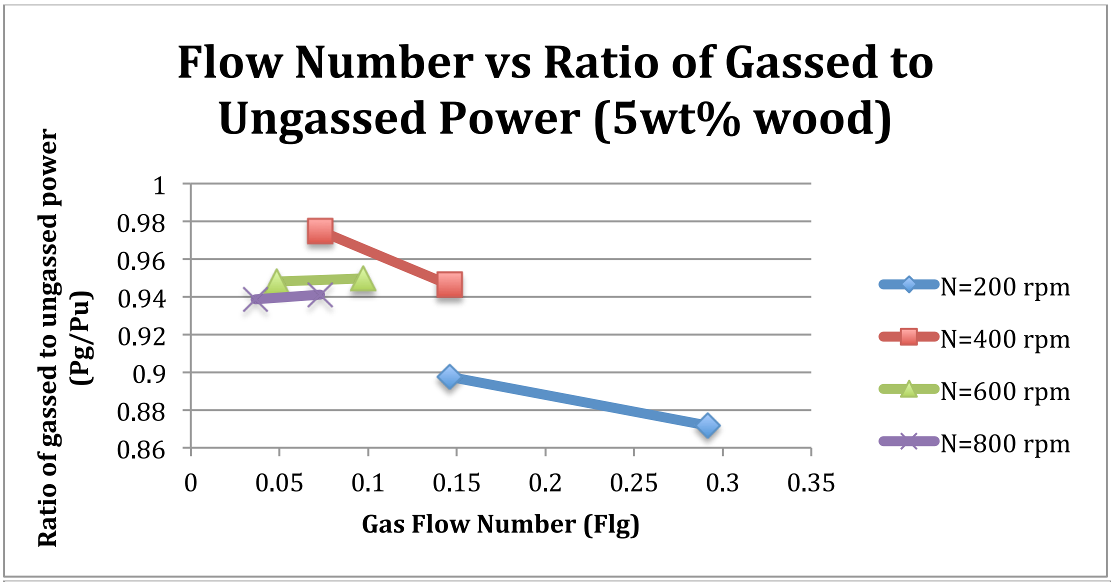
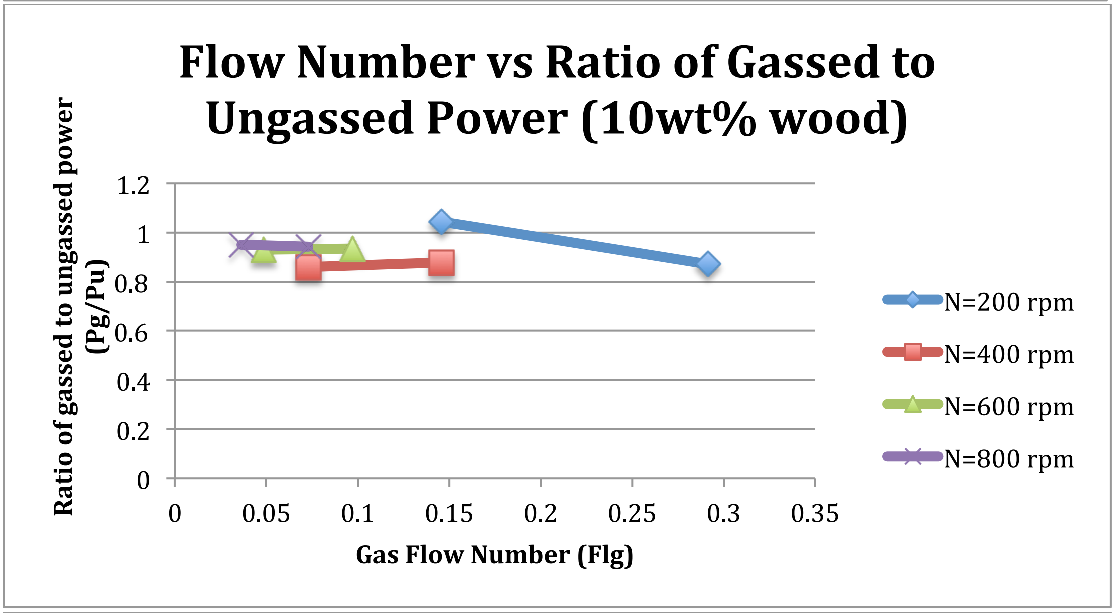


Figure 36 Flow Number versus Ratio of gassed to ungassed power

6.6.2 Experiments of using Pitched blade impeller





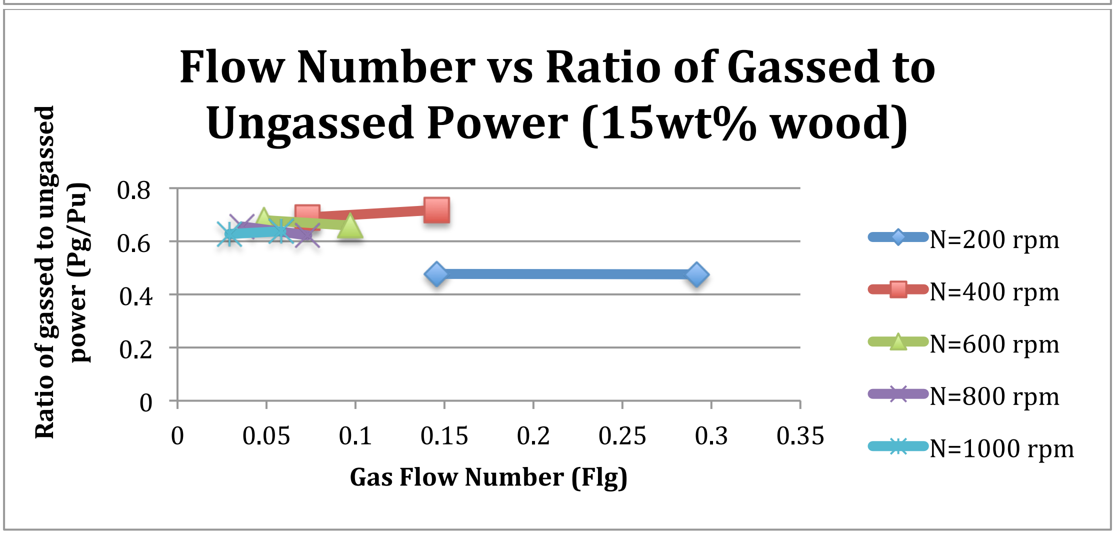


Figure 37 Flow Number versus Ratio of gassed to ungassed power

Typically increasing gas flow rate reduce power consumption because impeller might be partially covered by gas (flooded). There is little information about the systems similar to your so you can add " further investigation necessary because of complex rheology and morphology.

6.7 Future Work

This section covers some recommendations for future studies in light of interesting comments, thoughts and conclusions achieved from this study, which is presented in this thesis.

- ❖ Employing another form of wood pellets instead of using Brites wood pellets:

  First problem of this study was the settlement of wood particles on the base of stirred vessel, which was totally unexpected because wood is usually known as particles, which float on water. So the type of Brite wood pellets might be the reason, which caused the settlement condition in this study.

  Therefore, for future studies, it might be interesting to examine different form of wood pellets from different Companies.
- ❖ Investigation of current experiments with using solvent or catalyst:

  As long as, studying the rheology of a mixture plays as important role in a research. It would be desirable to measure the viscosity and particle sizes. In order to achieve this goal, it was necessary to use a solvent or catalyst to make wood pellets dissolve in water to become a paste. Therefore, for future works, there might be a good point to make a paste out of water and wood to carry on the investigation.
- ❖ The equilibrium time of five minutes which was a set mixing time for this study, can be increased for future works to see the difference between measured torques. Also by increasing mixing time there might be more reactions between water, wood pellet and air.

Nomenclature

N	Impeller speed (min^{-1})
N_{js}	Minimum impeller speed (min^{-1})
N_{jsg}	Minimum impeller speed (gassed) (min^{-1})
P	Power Drawn (Watt)
P_0	Power Number
T_q	Torque ($N \cdot m$)
μ	Viscosity (Pa.s)
ρ	Density (kg/m^3)
ρ_l	Density of liquid ($kg.m^{-3}$)
ρ_s	Density of solid ($kg.m^{-3}$)
T	Tank diameter (m)
t	Time (minute)
D	Impeller diameter (m)
d_p	Particle diameter (m)
C	Impeller clearance (m)
Re	Reynold Number
$\dot{\gamma}$	Shear Rate (s^{-1})
K_s	Metzner and Otto constant
n	Flow behaviour index
τ	Shear stress (Pas)
ε	Energy dissipation rate ($w.kg^{-1}$)
S	Shape factor
g	Gravitational acceleration ($m.s^{-2}$)
$\Delta\rho$	Solid-liquid density difference
X	Solid concentration by weight x 100
ν	Kinematic viscosity (Pa.s)

Tables

Table 5-i Power consumptions of unaerated system, using Rushton Turbine and Pitched blade impeller.

Impeller Type	Impeller Speed (rpm)	Power Draw (Watt) (5 wt%solid Concentration)	Power Draw (Watt) (10wt%solid Concentration)	Power Draw (Watt) (15wt%solid Concentration)
Rushton Turbine	200	1.65	1.96	1.88
Rushton Turbine	400	5.86	5.8	6.28
Rushton Turbine	600	14.45	13.82	14.45
Rushton Turbine	800	29.32	27.64	30.15
Rushton Turbine	1000	49.21	48.17	49.21
Pitched Blade	200	1.69	1.67	3.45
Pitched Blade	400	4.99	5.65	7.35
Pitched Blade	600	11.00	11.64	14.65
Pitched Blade	800	20.49	21.80	25.15
Pitched Blade	1000	33.84	35.70	39.34

Table 5-ii Power consumptions of aerater systems, using Rushton Turbine and Pitched blade impeller.

Impeller Type	Air Flow Rate (L.min^{-1})	Impeller Speed (rpm)	Power Draw (Watt) (5 wt%solid Concentratio)	Power Draw (Watt) (10 wt%solid Concentratio)	Power Draw (Watt) (15wt% solid Concentratio)
Rushton Turbine	10	200	1.57	1.57	1.67
Rushton Turbine	10	400	5.86	5.44	5.44
Rushton Turbine	10	600	13.82	13.19	12.56
Rushton Turbine	10	800	-	22.61	19.26
Rushton Turbine	10	1000	-	35.60	27.22
Rushton Turbine	20	200	1.54	1.59	1.88
Rushton Turbine	20	400	6.28	5.44	5.86
Rushton Turbine	20	600	16.33	13.82	11.93
Rushton Turbine	20	800	-	26.80	16.75
Rushton Turbine	20	1000	-	36.65	27.22
Pitched Blade	10	200	1.52	1.75	1.64
Pitched Blade	10	400	4.87	4.85	5.07
Pitched Blade	10	600	10.43	10.83	9.96
Pitched Blade	10	800	19.23	20.74	16.52
Pitched Blade	10	1000	-	-	24.69
Pitched Blade	20	200	1.48	1.45	1.64
Pitched Blade	20	400	4.72	4.96	5.28
Pitched Blade	20	600	10.44	10.88	9.66
Pitched Blade	20	800	19.28	20.55	15.65
Pitched Blade	20	1000	-	32.40	25.09

Table 5-iii Power consumption of unaerated system, using Helical ribbon impeller.

Impeller Speed (rpm)	Power Draw (Watt) (5 wt% solid Concentration)	Power Draw (Watt) (10 wt% solid Concentration)	Power Draw (Watt) (15 wt% solid Concentration)
35	0.26	0.23	0.26
65	0.56	0.49	0.57
95	0.91	0.81	0.98
125	1.24	1.12	1.37
155	1.55	1.4	1.78
185	1.91	1.78	2.28

Table 5-iv calculated power Numbers, using Rushton Turbine impeller.

Solid Concentration (wt%)	Air flow rate ($L.min^{-1}$)	Impeller speed (rpm)	Power Number
5	0	200	18.45
5	0	400	8.17
5	0	600	5.97
5	0	800	5.11
5	0	1000	4.39
5	10	200	17.52
5	10	400	8.17
5	10	600	5.71
5	20	200	17.28
5	20	400	8.76
5	20	600	6.74
10	0	200	21.53
10	0	400	8.01
10	0	600	5.60
10	0	800	4.72
10	0	1000	4.21
10	10	200	17.18
10	10	400	7.44
10	10	600	5.34
10	10	800	3.86
10	10	1000	3.11
10	15	200	17.41
10	15	400	7.44
10	15	600	5.60
10	15	800	4.58
10	15	1000	3.20
15	0	200	20.23
15	0	400	8.43
15	0	600	5.74
15	0	800	5.05
15	0	1000	4.22
15	10	200	17.98
15	10	400	7.30
15	10	600	4.99
15	10	800	3.23
15	10	1000	2.33
15	20	200	20.23
15	20	400	7.86
15	20	600	4.74
15	20	800	2.81
15	20	1000	2.33

Table 5-v calculated power Numbers, using Pitched blade impeller.

Solid Concentration (wt%)	Air flow rate ($L.min^{-1}$)	Impeller speed (rpm)	Power Number
5	0	200	26.75
5	0	400	9.83
5	0	600	6.41
5	0	800	5.04
5	0	1000	4.26
5	10	200	24.01
5	10	400	9.59
5	10	600	6.08
5	10	800	4.73
5	20	200	23.32
5	20	400	9.31
5	20	600	6.09
5	20	800	4.74
10	0	200	25.88
10	0	400	10.91
10	0	600	6.66
10	0	800	5.26
10	0	1000	4.41
10	10	200	27.04
10	10	400	9.38
10	10	600	6.20
10	10	800	5.00
10	15	200	22.54
10	15	400	9.58
10	15	600	6.22
10	15	800	4.95
10	15	1000	4.00
15	0	200	52.30
15	0	400	13.94
15	0	600	8.22
15	0	800	5.95
15	0	1000	4.77
15	10	200	24.98
15	10	400	9.61
15	10	600	5.59
15	10	800	3.91
15	10	1000	2.99
15	20	200	24.88
15	20	400	10.014
15	20	600	5.42
15	20	800	3.70
15	20	1000	3.04

Table 5-vi calculated power Numbers, using helical ribbon impeller.

Solid Concentration (wt%)	Impeller speed (rpm)	Power Number
5	35	1123.34
5	65	375.46
5	95	194.83
5	125	116.20
5	155	76.37
5	185	55.28
10	35	994.62
10	65	323.87
10	95	170.31
10	125	103.17
10	155	70.22
10	185	50.38
15	35	1080.95
15	65	365.64
15	95	201.74
15	125	123.58
15	155	84.20
15	185	63.40

Table 5-vii Minimum impeller speed for Rushton turbine impeller.

Solid concentration (w/w%)	Air flow rate (lit/min)	N_{js}(rpm)
5	0	470
5	10	230
5	20	190
10	0	750
10	10	410
10	20	380
15	0	-
15	10	-
15	20	-

Table 5-viii Minimum impeller speed of using Pitched blade impeller.

Solid concentration (w/w%)	Air flow rate (lit/min)	N_{js}(rpm)
5	0	370
5	10	350
5	20	300
10	0	730
10	10	650
10	20	600
15	0	-
15	10	-
15	20	-

Table 5-ix Minimum impeller speed for helical ribbon impeller.

Solid concentration (w/w%)	Air flow rate (lit/min)	N_{js}(rpm)
5	0	125
10	0	155
15	0	-

References

africaine, U. é. e. m. o. (2008). Sustainable Bioenergy Development in UEMOA Member Countries, **West African Economic and Monetary Union**.

Allen, T. (2003). Powder Sampling and Particle Size Determination, **Elsevier**.

Audrey (2012). **Structure of Wood;Society of Wood Science and Technology.Teaching Unit Number 1, Slide Set 2 [online]** Available from: http://www.swst.org/teach/teach1/structure1.pdf

Armenante, P. M. and E. U. Nagamine (1998). "Effect of low off-bottom impeller clearance on the minimum agitation speed for complete suspension of solids in stirred tanks." **Chemical Engineering Science 53**(9): 1757-1775.

Atherton, J., I. Houson, et al. (2011). **Understanding the Reaction. Process Understanding**, Wiley-VCH Verlag GmbH & Co. KGaA: 87-125.

Atiemo-Obeng, V. A., Penney, W. R. and Armenante, P. (2004) Solid–Liquid Mixing, in Handbook of Industrial Mixing: Science and Practice (eds E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta), John Wiley & Sons. pp. 543-584

Ayranci, I. and S. M. Kresta (2011). "Design rules for suspending concentrated mixtures of solids in stirred tanks." **Chemical Engineering Research and Design 89**(10): 1961-1971.

Askeland, D. R., et al. (2011). The Science & Engineering of Materials, **Cengage Learning.**

Brito De La Fuente, E., L. Choplin, et al. (1997). "Mixing With Helical Ribbon Impellers: Effect of Highly Shear Thinning Behaviour and Impeller Geometry." **Chemical Engineering Research and Design 75(1):** 45---52.

Blakeney, W. R. (1966). "The viscosity of suspensions of straight, rigid rods." **Journal of Colloid and Interface Science 22**(4): 324-330.

Bhattacharya, S., et al. (2010). "Computational modelling of industrial pulp stock chests." **The Canadian Journal of Chemical Engineering 88**(2): 295-305.

Brites. (2012). **The natural answer to a burning issue** [online]. Available from: http://www.brites.eu/ [Accessed May 2012]

Brown, D. A. R., Jones, P. N., Middleton, J. C., Papadopoulos, G. and Arik, E. B. (2004) Experimental Methods, in Handbook of Industrial Mixing: Science and Practice (eds E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta), John Wiley & Sons.pp. 145-256

Biermann, C. J. (1996). **Handbook of pulping and papermaking [online]**. Available from http://www.sciencedirect.com/science/book/9780120973620.

Chapman, C. M., A. W. Nienow, and M. Cooke (1983). Particle–gas–liquid mixing in stirred vessels: 1. Particle–liquid mixing, **Chem. Eng. Res. Dev**., 61, 71–81.

Chapple, D., et al. (2002). "The Effect of Impeller and Tank Geometry on Power Number for a Pitched Blade Turbine." **Chemical Engineering Research and Design 80**(4): 364-372.

Chase, W. C., et al. (1989). "Effects of freeness and consistency on the viscosity of hardwood and softwood pulp suspensions." **Tappi journal 72**(5): 199-204.

Chaouche, M. and D. L. Koch (2001). "Rheology of non-Brownian rigid fiber suspensions with adhesive contacts." **Journal of Rheology 45**: 369.

Cullen, P. J. (2009). **Food Mixing: Principles and Applications**, John Wiley & Sons.

Delaplace, G., et al. (2000). "Power Requirement when Mixing a Shear-Thickening Fluid with a Helical Ribbon Impeller Type." **Chemical Engineering & Technology 23**(4): 329-335.

Delaplace, G., J. C. Leuliet, et al. (2000). "Circulation and mixing times for helical ribbon impellers. Review and Experiments." **Experiments in Fluids 28(2):** 170-182.

Delaplace, G., R. Guerin, et al. (2006). "An analytical model for the prediction of power consumption for shear---thinning fluids with helical ribbon and helical screw ribbon impellers." **Chemical Engineering Science 61(10):** 3250-3259.

Derakhshandeh, B., et al. (2011). "Rheology of pulp fibre suspensions: A critical review." **Chemical Engineering Science 66**(15): 3460-3470.

Dieulot, J. Y., G. Delaplace, et al. (2002). "Laminar Mixing Performances of a Stirred Tank Equipped with Helical Ribbon Agitator Subjected to Steady and Unsteady Rotational Speed." **Chemical Engineering Research and Design 80(4):** 335-344.

Doran, P. M. (2013). **Bioprocess Engineering Principles**, Academic Press.

Dohi, N., T. Takahashi, et al. (2004). "Power consumption and solid suspension performance of large-scale impellers in gas–liquid–solid three-phase stirred tank reactors." **Chemical Engineering Journal 97**(2–3): 103-114.

Doitpoms, L. G., Sonya Rachel Pemberton (2006). **The structure and mechanical behaviour of wood [online].** Available from: http://www.doitpoms.ac.uk/tlplib/wood/index.php [Accessed on 24 May 2012]

Engelund, E. T. (2011). Wood – water interactions,Linking molecular level mechanisms with macroscopic performance. **Department of Civil Engineering, Technical University of Denmark. Phd:** 170.

Ein-Mozaffari, F., et al. (2007). "Optimization of rectangular pulp stock mixing chest dimensions using dynamic tests." **Tappi journal 6**(2): 24-30.

Ein-Mozaffari, F., et al. (2003). "Performance and design of agitated pulp stock chests." **Appita journal 56**(2): 127-133.

Ein-Mozaffari, F., et al. (2004). "The Effect of Operating Conditions and Design Parameters on the Dynamic Behaviour of Agitated Pulp Stock Chests." **The Canadian Journal of Chemical Engineering 82**(1): 154-161.

Ende, D. J. A. (2011). **Chemical Engineering in the Pharmaceutical Industry: R&d to Manufacturing**, John Wiley & Sons.

Ford, C., et al. (2006). "Simulation of mixing dynamics in agitated pulp stock chests using CFD." **AIChE journal 52**(10): 3562-3569.

Fu, D., G. Mazza, et al. (2010). "Lignin Extraction from Straw by Ionic Liquids and Enzymatic Hydrolysis of the Cellulosic Residues." **Journal of Agricultural and Food Chemistry 58**(5): 2915-2922

Forest Product Laboratory (2010). **Wood Handbook - Wood as an Engineering Material**, U.S. Department of Agriculture.

Garcia, B. (2012). **Benefits of Using Biomass** [online]. Available from: http://www.streetdirectory.com/travel_guide/134753/technology/benefits_of_using_biomass.html
[accessed on 24 Apr 2012]

Ghionzoli, A., et al. (2007). "The effect of bottom roughness on the minimum agitator speed required to just fully suspend particles in a stirred vessel." **Chemical Engineering Research & Design 85**(A5): 685-690.

Gomez, C., et al. (2010). "Carbopol as a model fluid for studying mixing of pulp fibre suspensions." **Chemical Engineering Science 65**(3): 1288-1295.

Gray, D. J. (1987) Impeller clearance effect on off- bottom particle suspension in agitated vessels. Chem. Eng. Community. 61, 151—158.

Grenville, R. K. and Nienow, A. W. (2004) Blending of Miscible Liquids, in Handbook of Industrial Mixing: Science and Practice (eds E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta), John Wiley & Sons. pp.507-542.

Hemrajani, R. R. and Tatterson, G. B. (2004) Mechanically Stirred Vessels, in Handbook of Industrial Mixing: Science and Practice (eds E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta), John Wiley & Sons. pp. 345-389

Hosseini, S., et al. (2010). "Study of solid–liquid mixing in agitated tanks through electrical resistance tomography." **Chemical Engineering Science 65**(4): 1374-1384.

Jafari, R., et al. (2012). "Characterization of Minimum Impeller Speed for Suspension of Solids in Liquid at High Solid Concentration, Using Gamma-Ray Densitometry." **International Journal of Chemical Engineering 2012**: 15.

Kamimura, K., H. Kuboyama, et al. (2012). "Wood biomass supply costs and potential for biomass energy plants in Japan." **Biomass and Bioenergy 36**(0): 107-115.

Kunitz, M. (1926). "AN EMPIRICAL FORMULA FOR THE RELATION BETWEEN VISCOSITY OF SOLUTION AND VOLUME OF SOLUTE." **The Journal of General Physiology 9**(6): 715-725.

Lange, H., et al. (2013). "Oxidative upgrade of lignin – Recent routes reviewed." **European Polymer Journal 49**(6): 1151-1173.

Lucia, L. A. (2007). "A REVIEW OF BIOMASS AS THE NEW FEEDSTOCK FOR THE MATERIAL AND ENERGY NEEDS OF THE 21ST CENTURY."

MacKay, D. G., B. J. W. Cole, et al. (2009). "**Potential Markets for Chemicals and Pharmaceuticals from Woody Biomass in Maine**."

Marshall, E. M. and Bakker, A. (2004) Computational Fluid Mixing, in Handbook of Industrial Mixing: Science and Practice (eds E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta), John Wiley & Sons. pp.257-341

Metzner, A. B., and R. E. Otto (1957). Agitation of non-Newtonian fluids, *AIChE J.,* **3,** 3–10.

Moniruzzaman, M. and T. Ono (2013). "Separation and characterization of cellulose fibers from cypress wood treated with ionic liquid prior to laccase treatment." **Bioresource Technology 127**(0): 132-137.

Nienow, A. W. (1968) Suspension of solid particles in turbine-agitated, baffled vessels. Chem. Engng Sci. 23, 1453—1459.

Nienow, A. W. (1997). "On impeller circulation and mixing effectiveness in the turbulent flow regime." **Chemical Engineering Science 52(15):** 2557---2565.

Nienow, A. W. and W. Bujalski (2002). "Recent Studies on Agitated Three-Phase (Gas–Solid–Liquid) Systems in the Turbulent Regime." **Chemical Engineering Research and Design 80**(8): 832-838.

Oberg, E., et al. **Machinery's Handbook (28th Edition) & Guide to Machinery's Handbook**, Industrial Press.

Paul, E. L., V. A. Atiemo-Obeng, et al. (2004). **Handbook of Industrial Mixing - Science and Practice**, John Wiley & Sons. pp. xxxvi

Plater, A. J. (1993). "Principles, methods, and application of particle size analysis edited by James P.M. Syvitski. Cambridge University Press, Cambridge, 1991. No. of pages: 368. Price £45.00 (hardback). ISBN 0521 364 728." **Geological Journal 28**(1): 95-96.

Rangan, C.S., G.R. Sarma, V.S.V Mani.(1997). **Instrumentation : Devices and Systems,2e**, Tata McGraw-Hill Publishing Co.

Rieger, F., et al. (1986). "Homogenization efficiency of helical ribbon agitators." **The Chemical Engineering Journal 33**(3): 143-150.

Sagisaka, M. (2007). **Sustainable Biomass Utilization Vision in East Asia, ERIA Research [online]**. Available from:
http://www.eria.org/research/images/pdf/PDF%20No.6-3/No.6-3-4%20Chap%203%20Bioamss.pdf
[Accessed on 17 Jun 2012]

Shekhar, S. M. and S. Jayanti (2003). "Mixing of pseudoplastic fluids using helical ribbon impellers." **AIChE Journal 49(11):** 2768---2772.

Sharratt, P. N. (1996). Handbook of batch process design. London, Chapman & Hall. pp. 107-138

Stitt, E. H. and Simmons, M. J. H. (2011). **Scale-Up of Chemical Reactions in Process Understanding:** For Scale-Up and Manufacture of Active Ingredients (ed I. Houson), Wiley-VCH Verlag GmbH & Co. KGaA: 155-198.

Tran, H. and E. K. Vakkilainnen (2008). **THE KRAFT CHEMCIAL RECOVERY PROCESS**.

Wiley-Blackwell (2009), **Biomass As A Source Of Raw Materials, *ScienceDaily***, [online]. Available from:
http://www.sciencedaily.com/releases/2009/05/090512102549.htm
[Accessed Aug 2012]

Yackel, D. C. (1990). Pulp and Paper Agitation: The History, Mechanics, and Process, **Technical Association of the Pulp and Paper Industry** (TAPPI).

Ziemann, F., et al. (1994). "Local measurements of viscoelastic moduli of entangled actin networks using an oscillating magnetic bead micro-rheometer." **Biophysical Journal 66**(6): 2210-2216.

Zhu, Y. and J. Wu (2002). "Critical Impeller Speed for Suspending Solids in Aerated Agitation Tanks." **The Canadian Journal of Chemical Engineering 80**(4): 1-6.

Zwietering, T. N. (1958) Suspending solid particles in liquids by agitators. Chem. Engng Sci. 8, 244—253.